VOLUME XXIV NUMBER 7

THE

JOURNAL OF GEOLOGY

OCTOBER-NOVEMBER 1916

THE GENESIS OF LAKE AGASSIZ:[1] A CONFIRMATION

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INTRODUCTION

In a paper published in the *Journal of Geology* in 1896, J. B. Tyrrell stated that the results of his field work in the region lying to the west and southwest of Hudson Bay showed that—

> the Keewatin glacier seems to have retired northward well into Manitoba and possibly even beyond the northern limit of that province before it was joined by the eastern glacier. When they united the water was ponded between the

[1] Published by permission of the Director of the Geological Survey of Canada.

fronts of the two glaciers to the north and northeast and the high ground to the south and west. Thus Lake Agassiz had its beginning. Its waters rapidly rose until they overflowed southward into the valley of the Mississippi and then gradually declined as River Warren deepened its channel.[1]

By his more recent work in the region lying to the south of Hudson Bay, Tyrrell has shown that the last invasion of glacial ice in that region was by an ice sheet which advanced in a southwesterly direction and overlapped a portion of the area previously occupied by an ice sheet which he named the Patrician Glacier. This last advance of the ice extended in a southwesterly direction at least as far as the headwaters of the Severn River and in a westerly direction approximately as far as the Hayes River, where it was met by a readvance of the Keewatin glacier.[2]

Field work done by the writer during portions of the seasons of 1913 and 1914 in the vicinity of the Rainy River and Lake of the Woods, Ontario, has brought forth evidence which confirms Tyrrell's view that Lake Agassiz had at first a rising stage, due to the blocking of the northward drainage, and later subsided, and that, during the entire existence of the lake, the ice border was far to the north and northeast. This conception of the life-history of Lake Agassiz differs radically from that of Warren Upham, by whose work Lake Agassiz is best known, and whose interpretation has been most widely accepted. The object of the present paper is to present the evidence which confirms Tyrrell's view as to the genesis of Lake Agassiz and to point out that the acceptance of this view has an important bearing upon the question of the character and cause of the epeirogenic movements which deformed the shore lines of Lake Agassiz.

UPHAM'S CONCEPTION OF THE LIFE-HISTORY OF LAKE AGASSIZ

Glacial Lake Agassiz is best known from the work of Warren Upham, the results of which were published in 1895 by the United States Geological Survey as *Monograph 25*. Upham's field work in connection with the investigation of the basin of Lake Agassiz was done some thirty years ago and was largely confined to the

[1] J. B. Tyrrell, "The Genesis of Lake Agassiz," *Jour. Geol.*, IV (1896), 813.

[2] J. B. Tyrrell, "The Patrician Glacier South of Hudson Bay," *Congrès Géologique International, Canada, 1913, Compte-Rendu* (Ottawa, Canada, 1914), pp. 523–34.

western or prairie portion of the basin. At that time little was known of the extension of the lake in the northern portion of the state of Minnesota or in the adjoining portions of Canada, for much of this region was densely wooded, largely unsettled, and difficult of access. At that time, also, the general conception was that during Pleistocene time the Laurentide glacier occupied the greater portion of Central and Northwestern Canada. It was not until some time later that the subdivision into Keewatin and Labradorean ice fields was recognized.

Upham believed, as the result of his investigations, that the northward drainage of Red River valley and adjacent areas was ponded between the retreating front of the Laurentide glacier on the north and northeast and the divide on the south, that the lake had at first a small beginning in the southern part of the basin and gradually grew in size as the ice withdrew toward the northeast, and that a great series of moraines was deposited in the waters of the lake at stages of halt or slight readvance during the general retreat of the ice sheet. He found that the lake, during its higher stages, discharged southward to the Mississippi along the course of the present Lake Traverse and Minnesota River valleys. During the operation of the southern outlet several strong shore lines of the lake were developed. As the ice retired and uplift took place, lower outlets were opened toward the northeast and other and lower beaches were developed in the northern part of the basin. He also showed that beaches which are single in the southern portion of the basin split into series in the northern portion of the basin and rise differentially toward the north-northeast, the highest being most upwarped and the lowest least, thus proving that differential elevation of the land went on during the existence of the lake.[1]

DIFFICULTIES IN ACCEPTING UPHAM'S INTERPRETATION

Some of the difficulties involved in accepting Upham's interpretation of the life-history of Lake Agassiz were pointed out by T. C. Chamberlin. It was found by Upham that the uppermost or Herman beach was continuous for a long distance northward

[1] Warren Upham, "The Glacial Lake Agassiz," *U.S. Geol. Survey, Monograph 25*, 1895.

and that it overrode three prominent moraines which marked halts or readvances of the ice front. Upham supposed that the Herman beach represented the whole time of the formation of the several moraines and of the retreat of the ice front for at least 250 miles, in spite of the fact that he found the beach to be not very massive and not very notably stronger in the southern than in the northern portion. Recognizing this difficulty, Chamberlin suggested that "the whole history of Lake Agassiz may not have fallen within the period of stationary or rising crustal movement but that the early part of it may have taken place during the latter portion of the period within which the crust was being depressed."[1] In this way it may be supposed that shore lines were formed at early stages of the lake but were later submerged. The uppermost Herman beach would have been formed at the time of maximum submergence. It would be all of one age and would represent a comparatively short time.

Another difficulty arises from the character of the deposits laid down in the basin of the lake. Upham held that the greater part of these deposits were derived from the ice sheet and its inclosed drift—a necessary inference from his interpretation of the history of the lake. But he found that "bowlders are absent or exceedingly rare in the beaches, deltas, and finer lacustrine sediments."[2] If it is true that a series of moraines was deposited in the lake, and if the sediments of the lake basin were largely derived from the ice sheet, it seems highly probable that berg deposits would form an important part and that bowlders would be included in the sediments.

A serious difficulty also arises if Upham's interpretation of the mode of origin of the sediments which occur in Red River valley is accepted. Upham held that these sediments are recent fluvial deposits laid down in local depressions and on flood plains of streams after the disappearance of Lake Agassiz. The deposits, he states, "have commonly greater thickness and extent than the underlying silt of glacial Lake Agassiz."[3] In the southern portion of the basin they are in places underlain at considerable depths by "sheets of turf,"[4] etc., apparently indicating the presence of an old soil. The

[1] "The Glacial Lake Agassiz," *U.S. Geol. Survey, Monograph 25*, p. 245.

[2] *Ibid.*, pp. 183 and 201. [3] *Ibid.*, p. 202. [4] *Ibid.*, p. 253.

great thickness and extent of these deposits and the occurrence of "sheets of turf" in their lower portions seem difficult of explanation on the assumption that they are "recent fluvial deposits."

All these difficulties disappear, however, if it is considered, as the evidence seems to show, that Lake Agassiz had at first small beginnings in Red River valley and gradually rose until it overflowed to the south, owing to a blocking of the northward drainage by an advance of the ice, and that the ice advanced only into the northern portion of the basin, so that the whole southern part of the lake was practically free from ice during the entire existence of the lake.

RECORDS OF LAKE AGASSIZ IN RAINY RIVER–LAKE OF THE WOODS DISTRICT

Geographical relations of the district.—The eastern portion of Rainy River–Lake of the Woods district lies about midway between Lake Superior and the Red River of the province of Manitoba. The Rainy River connects Rainy Lake and Lake of the Woods and for a distance of 82 miles forms the international boundary between the state of Minnesota and the adjoining portion of the province of Ontario. The Rainy River, the main stream of the region, flows westward to Lake of the Woods, which drains northwestward to Lake Winnipeg and thence to Hudson Bay, so that the whole area lies within the Hudson Bay drainage system. The altitude of Rainy Lake is 1,107 feet and of Lake of the Woods 1,060 feet above the sea, and the general altitude of the plain bordering the Red River on the west is about 200 feet lower. The southern portion of Lake of the Woods is shallow and is generally bordered by drift deposits. The divide southwest of the lake, separating the lake basin from that of the Red River on the west, is low and for some distance is less than 30 feet above Lake of the Woods. On the northwest, near Northwest Angle, the divide is also only a few feet above the level of the lake, so that the plains of Manitoba and northern Minnesota are practically continuous on the southwest and northeast into the southern portion of the Lake of the Woods basin. In southeastern Manitoba, and west of the southern portion of Lake of the Woods, the continuity of the plain's surface is broken

by a relatively high area which rises to a maximum height of about 200 feet above the general level of the plains. The area lying between Rainy Lake and Lake of the Woods is so deeply drift-covered that comparatively few solid-rock exposures occur. The surface has generally very slight relief, and slopes gently toward the west, so that the area really forms a portion of the eastward extension of the wooded portion of the prairie plains of Manitoba and northern Minnesota, from which it is separated by the shallow basin of the southern portion of Lake of the Woods. In the northern portion of Lake of the Woods and north of a line drawn from the central part of the lake southeastward to Rainy Lake, the country is generally rocky and has comparatively little drift covering.

Till sheets.—There are at least two distinct till sheets in the district. The upper and younger is distinguished from the lower and older till sheet by the calcareous nature of its materials, and by the presence in it of bowlders of limestone and other rocks which are known to outcrop in Manitoba, but not in the district itself nor in the region lying to the northeast. Striae observed on the bedrock beneath the till sheet trend southeastward or eastward. These striae were not seen to be crossed by later striae, and no till was seen to overlie this till sheet. It seems evident, therefore, that the calcareous till was deposited by a lobe of the Keewatin glacier and that the area in which the calcareous till occurs was not overridden by an advance of ice from the northeast at a later time.

The lower and older till sheet was deposited by an ice sheet advancing from the northeast. This is shown by the southwestward trend of striae on the bedrock underlying this till sheet and by the fact that the till contains no limestone similar to that which occurs in the upper sheet. Associated with the lower till sheet are considerable deposits of fluvio-glacial sands and gravels which also contain no limestone. No evidence was seen which would suggest that there was any considerable lapse of time between the deposition of the two till sheets, and it is presumed that they were nearly contemporaneous in age and were deposited during the Wisconsin stage of glaciation.

Laminated stony clays.—A series of laminated clays, containing in places striated stones and bowlders, occurs in the district. The

clays overlie and in the eastern portion of the district also underlie the calcareous till, with which they are closely associated. In some sections there is a sort of transition upward from the unstratified till into the laminated clays; that is, in the lower portion of the clays distinct laminae of clay are separated by unstratified stony material resembling the underlying till. The stony layers at the base rarely exceed a few inches or at most a foot in thickness and rapidly die out, so that "the transition beds" are, as a rule, only 4 or 5 feet thick. The laminated clays in the district range in altitude from 1,060 up to at least 1,200 feet, but they are generally only a few feet in thickness. These clays were deposited in a glacial marginal lake which is here referred to as Early Lake Agassiz. This lake was associated with an advance of the Keewatin glacier which deposited the calcareous till in the region. The clays were in part deposited during the time of advance of the ice sheet, for in places till overlies the clays. This relation is well seen in the sections exposed in the gravel pit one and one-half miles west of Fort Frances, where 8 feet of calcareous till overlie laminated clays, which are again underlain by non-calcareous, fluvio-glacial sands and gravels. The laminated clays were also in part deposited during the time of retreat of the ice. Early Lake Agassiz was, however, largely if not wholly drained before the later Lake Agassiz came into existence, for the desposits of Lake Agassiz rest unconformably on the calcareous till and on the closely related laminated clays.

Deposits of Lake Agassiz.—Numerous raised beaches of Lake Agassiz occur in the district, at altitudes ranging from 1,100 to 1,200 feet. The strongest and best-developed beach extends northward for some distance from the vicinity of the town of Rainy River. The altitude of this beach near the town of Rainy River is 1,117 feet. Ten miles northeast of this locality its altitude is about 1,125, and twenty-four miles northeast its altitude is about 1,140. Higher beaches occur at various altitudes up to at least 1,200 feet. A comparatively small part of the drift-covered area lying between Rainy Lake and Lake of the Woods rises more than 1,200 feet, but in the northern portion of Minnesota immediately south of Rainy River district drift-covered areas rise considerably higher. In this

area a number of beaches rising well above 1,200 feet have been found by Mr. Leverett, who states that bars of gravel and sand formed by the waters of Lake Agassiz occur on the highest points of Beltrami Island.[1]

The lacustrine deposits of Lake Agassiz in the district occupy areas of considerable extent and are in places at least 30 feet thick. They are generally even-bedded but not strongly laminated. In places they are characterized by an irregular alternation of sandy and clayey layers and occasionally thin gravelly layers. The beds are in places more sandy toward their base than in their upper portion, and are frequently ripple-marked but not cross-bedded. The material is more oxidized than that of the older laminated stony clays, and there can be little doubt that the material was derived from erosion of land surfaces by wave and stream action. The sandy ripple-marked beds underlying clay, and the occurrence of gravelly layers interbedded with sandy and clayey layers are explained by the fact that the sediments were deposited in a rising body of water. The lacustrine beds are also characterized by the presence, in their lower portions at least, of fossil fresh-water shells. Fossil fresh-water shells also occur in some of the beach ridges at various altitudes up to 1,149 feet, or 88 feet above Lake of the Woods.

Unconformity at the base of Lake Agassiz sediments.—The evidence found in Rainy River district, which confirms Tyrrell's contention that Lake Agassiz had at first a rising stage, is based largely on the fact that the sediments deposited in Lake Agassiz rest unconformably upon the underlying deposits; that is, a period of erosion intervened after the deposition of the calcareous till and associated laminated stony clay, and before the later lacustrine sediments were laid down.

This is well shown in numerous sections exposed along the Rainy River and around the shores of the southern portion of Lake of the Woods. Fig. 1 illustrates the character of one of these sections which has been exposed by wave erosion on the present shore of Lake of the Woods at its southern side. At the base a

[1] Frank Leverett, "Surface Formations and Agricultural Conditions of Northwest Minnesota," *Minn. Geol. Soc., Bull. No. 12*, 1915, p. 37.

small thickness of calcareous till is exposed, passing up into laminated, stony clay which is overlain unconformably by Lake Agassiz lacustrine clays containing fresh-water shells. The contact is a wave-cut plain. The lacustrine deposits above the wave-cut plain are clayey in character and evenly and thinly bedded, so that it is evident that the water must have risen to a considerable height to permit of such deposition. In places around the southeastern portion of Lake of the Woods these lacustrine deposits are at least

FIG. 1.—Section exposed on south shore of Lake of the Woods, showing at the bottom calcareous till passing upward into laminated, stony clays unconformably overlain by Lake Agassiz lacustrine clays. The contact is a wave-cut plain.

30 feet thick and rise to an altitude higher than the divide separating the Lake of the Woods basin from that of the Red River on the west. Furthermore, the first strong raised beach above the level of Lake of the Woods, at the level of which the water must have stood, if not at some higher level, when the lacustrine deposits were laid down, is in the southern portion of the district from 45 to 55 feet above the level of Lake of the Woods; and this beach passes over the divide to the southwest of the lake.[1] Hence it follows that these lacustrine deposits were not laid down in a local lake

[1] *Minn. Geol. Survey, Bull. No. 12*, 1915 (map).

but in a body of water which covered not only the Rainy River and Lake of the Woods districts but also occupied Red River valley, and that this was the last great glacial-marginal lake in the region, viz., Lake Agassiz.

Numerous sections also show that weathering and erosion took place during the interval of erosion before the deposition of Lake Agassiz sediments. This is well shown in sections along the Rainy River from one to three miles below the town of Rainy River. In places, small stream valleys were eroded and later partially or wholly filled with lacustrine deposits. This relation is well seen in the small creek valley which enters the Rainy River three miles below Fort Frances. In one place, on Buffalo Point on the southwest side of Lake of the Woods, thin peaty bands occur in the lower portion of Lake Agassiz deposits.

The sections exposed on the south shore of Lake of the Woods (Fig. 1) afford a demonstration that the water must have risen to a sufficient height to permit of the deposition of the fine lacustrine clays overlying the old wave-cut beach, and it is clear that these waters formed part of Lake Agassiz during a rising stage. There is evidence in the district that the waters rose through a vertical interval of at least 60 feet; for the lake clays are unconformable on the underlying sediments throughout this vertical interval. The highest shore line found in Rainy River district has an altitude of 1,200 feet. During the highest stages of the lake, practically the entire district was submerged and the highest shore line, if there had been land high enough to have received it, would have a present altitude of approximately 1,350 feet, as estimated from Upham's determination of the highest beaches in other parts of the basin. It is not certain that the water rose to the level of the highest shore lines recognized in other portions of the basin; but it seems probable that it rose to the uppermost strong beach (Herman), because this beach, as already stated, is continuous for a long distance northward and is apparently all of one age. It is possible that the Milnor beach which Upham found to be traceable for only a short distance in the southern part of the basin marks a shore line of Early Lake Agassiz, but the extent of this lake or of any of its shore lines is not definitely known. This lake was largely drained

before Lake Agassiz came into existence and its sediments are buried beneath those of Lake Agassiz.

It is at least certain that the waters of Lake Agassiz stood at one time at about the present level of Lake of the Woods, and that they later rose considerably higher. It seems probable also that the lake which preceded Lake Agassiz was almost completely drained, and that Red River valley was a land surface before the latest advance of the ice brought Lake Agassiz into existence; for the character of the deposits in Red River valley, which Upham[1] regarded as post-Lake Agassiz fluvial deposits, suggests rather that they are lacustrine deposits and that they are unconformable on the underlying sediments.

Regarding these deposits Upham stated:

> Thus the occurrence of shells, rushes and sedges in these alluvial beds at McCauleyville, Minnesota, 32 and 45 feet below the surface or about 7 and 20 feet below the level of Red River, of sheets of turf, many fragments of decaying wood and a log a foot in diameter at Glyndon, Minnesota, 13 to 35 feet below the surface, and numerous other observations of vegetation elsewhere along the Red River valley in these beds, demonstrate that Lake Agassiz had been drained away, and that the valley was a land surface subject to overflow by the river at its stages of flood when these remains were deposited.[2]

He also stated: "The deposits have commonly greater thickness and extent than the underlying silt of glacial Lake Agassiz."

It is evident that a land surface existed in Red River valley before these sediments were laid down; but it seems probable that the sediments are largely lacustrine in origin and not fluvial. G. M. Dawson, in describing the section across Red River valley near the international boundary stated that the valley is floored with a fine silty deposit, a portion of the upper layers of which may have been formed by the overflow of the river itself. He described the typical deposit as of great thickness and consisting of fine yellowish, marly, and arenaceous clay, holding considerable calcareous matter, and effervescing freely with an acid.[3] The great extent and thickness and the high calcareous content of the clays

[1] Warren Upham, *U.S. Geol. Survey, Monograph 25* (1895), p. 253.

[2] *Ibid.*, p. 202.

[3] G. M. Dawson, *Report on the Geology and Resources of the Region in the Vicinity of the Forty-ninth Parallel*, 1875, pp. 248–49.

would seem to show that they are lacustrine in origin and not fluvial. It seems probable that they are Lake Agassiz deposits and that they are unconformable upon the underlying sediments.

It is concluded, therefore, with Tyrrell, that after the retreat of the Keewatin glacier well toward the north there was comparatively free drainage to the north and that a later advance of the ice from the northeast was met by a slight readvance of the Keewatin glacier, which resulted in the ponding of the northward drainage and the inception of Lake Agassiz. It is not certain just how far the latest advance of the ice extended. It did not reach Rainy River district, for the calcareous till derived from Manitoba is not overlain by till derived from the northeast, and the southeastward- and eastward-bearing striae are not crossed by later striae. At Stony Mountain, near Winnipeg, southeastward-bearing striae cross striae trending nearly south, but are not themselves crossed by later striae. Tyrrell found that along the east side of Lake Winnipeg southwestward-bearing striae cross earlier striae bearing nearly southward.[1] Tyrrell[2] also held that the "Winnipeg Moraine" represented by islands in Lake Winnipeg and developed in places along the western shore of the lake marked the termination of the Labradorean glacier. It seems evident that during the life of the last great glacial marginal lake of the region, viz., Lake Agassiz, the ice margin in Manitoba was at no time farther south than the southern portion of Lake Winnipeg, and that the whole southern portion of the lake was practically free from ice. Lake Agassiz was associated with a readvance of the ice sheet, chiefly of the Labradorean glacier at a very late time during the Wisconsin stage of glaciation, and its disappearance followed the final withdrawal of ice sheets from the region.

BEARING OF THE LIFE-HISTORY OF LAKE AGASSIZ ON THE QUESTION OF THE CHARACTER AND CAUSE OF THE DIFFERENTIAL UPLIFT

If it is true, as seems probable, that during the existence of Lake Agassiz the ice border was far north of the southern end of the lake, this fact has an important bearing on the character and

[1] J. B. Tyrrell, *Amer. Geol.*, VIII, 21.

[2] *Bull. Geol. Soc. Amer.*, XXIII (1911), 733.

cause of the differential uplift which is shown to have taken place by the deformation of the shore lines of the lake.

It is known that the whole of the southern portion of the Lake Agassiz basin was affected by uplift but that the region south of the southern outlet of the lake was unaffected, for the abandoned shore line of Lake Dakota in this region is apparently nearly horizontal.[1] That is, there is a sort of "hinge-line" here. The location of this "hinge-line" was not due to "quick recovery of the crust by uplift" following removal of the ice from the immediate neighborhood, for the ice border was at least 250 miles north of the location of the "hinge-line."

The question also arises whether, as Chamberlin suggested, the land was being depressed during the time of advance of the latest ice sheet. It would be possible to determine this if the present altitude with respect to sea-level of the beaches which were made during the rising stage of the lake could be determined. It was found in Rainy River district that the strongest beach of Lake Agassiz apparently marks a long stand of the waters during the rising stage and again during the subsiding stage; for the beach deposits show evidence of having been partly eroded and spread out by the rising waters and beach ridges having a slightly different trend were later built on the older deposits. This would seem to show that the land was already depressed during the rising stage of the lake, but the evidence is not very conclusive. In the case of the "fossil" shore line seen in sections along the south shore of Lake of the Woods (see Fig. 1), it was found that the beach maintains the same altitude in a direction corresponding to the trend of the isobases of the beaches formed during the subsiding stage of Lake Agassiz. It is not known whether it rises toward the northeast, for unfortunately no record of its occurrence could be found in the northern part of Lake of the Woods.

The evidence suggests, but does not prove, that if, as seems probable, the uplift of the land was due to isostatic readjustment following the removal of the burden of the ice sheets, there was no close sympathetic relation; but that uplift lagged[2] considerably

[1] *U.S. Geol. Survey, Monograph 25*, p. 267.

[2] J. Le Conte, *Bull. Geol. Soc. Amer.*, II (1891), 329–30; W. B. Wright, *The Quaternary Ice Age*, 1914.

behind the removal of the great mass of the Wisconsin ice sheets and was only completed after the final retreat following the latest advance of the ice.

SUMMARY

Evidence bearing on the life-history of Lake Agassiz, found in the Rainy River–Lake of the Woods district, Ontario, confirms Tyrrell's conclusion that Lake Agassiz had at first a rising stage. The evidence is based largely on the fact that an unconformity exists at the base of the Lake Agassiz lacustrine sediments. The lake was associated with the latest advance of ice sheets, chiefly of the Labradorean glacier, during the Wisconsin stage of glaciation. An earlier glacial marginal lake, which is herein referred to as Early Lake Agassiz, was associated with a lobe of the Keewatin glacier; but this lake was largely if not wholly drained before Lake Agassiz came into existence. The latest advance of the ice into the Lake Agassiz basin did not extend farther south than the southern portion of Lake Winnipeg, so that the ice border of Lake Agassiz was at least 250 miles north of the southern end of the lake during the entire existence of the lake.

The acceptance of this interpretation of the genesis of Lake Agassiz has an important bearing on the question of the character and cause of the differential uplift which is shown to have affected the region by the deformation of the shore lines. The evidence suggests, but does not prove, that if the uplift was due to isostatic readjustment following the removal of the burden of the ice sheets, there was no close sympathetic relation, but that, as Le Conte and Wright have supposed, uplift lagged considerably behind and was only completed after the final retreat following the latest advance of the ice sheets of the Wisconsin stage of glaciation.

THE LOWER EMBAR OF WYOMING AND ITS FAUNA

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About ten years ago Mr. N. H. Brown sent me a few *Helodus* teeth from the Embar limestone near Lander, Wyoming, and in the summer of 1911 I had the good fortune to discover a rather abundant fish fauna in the same region and on Bull Lake Creek. In the former region the fossils occur about 25 feet from the bottom of the formation and their vertical range is little more than 3 feet, while in the latter they are found at from 35 to 38 feet from the bottom.

Blackwelder[1] and Woodruff[2] have reported two distinct faunas from the Embar, the upper of which Girty[3] refers to the Permian, but the fauna reported here is older and entirely distinct from the other two. Collections from bottom to top of the Embar in several localities show only one species common to the fish horizon and the upper horizons.

DESCRIPTION OF THE EMBAR LIMESTONE

The Embar formation lies conformably, for the most part, below the Chugwater formation on the eastern slope of the Wind River Mountains and without apparent unconformity above the Tensleep sandstone. In the Big Popo Agie region, near Lander, it is about 400 feet thick, is largely limestone, and bears three and perhaps more phosphate beds. The lowest bed is 23 feet from the bottom, ranges from 1 foot to 5 or 6 feet in thickness, and bears fish remains and *Orbiculoidea utahensis* in abundance. This bed has been traced some 15 miles southeastward along the strike and about 5 miles nothwestward. I have examined the same bed on

[1] Eliot Blackwelder, "New or Little Known Paleozoic Faunas from Wyoming and Idaho," *Am. Jour. Sci.*, XXXVI (1913), 177–79.

[2] E. G. Woodruff, "The Lander Oil Field," *U.S. Geol. Surv., Bull. 452* (1913), pp. 12–14.

[3] *Ibid.*, p. 13.

the North Fork of Little Wind River, 27 miles to the northwest, and on Bull Lake Creek, 35 miles to the northwest. On Bull Lake Creek it is 38 feet from the bottom and 3 feet 6 inches in thickness. This is probably the same bed that Blackwelder describes as occurring in Dinwoody Canyon 29 feet 8 inches from the bottom, 2 feet 2.5 inches thick, and containing *Lingulodiscina utahensis*. Wherever the bed was examined it contained fish remains, and *Orbiculoidea utahensis* in abundance.

In Big Popo Agie Canyon a 4-inch phosphate bed, as it was measured, but probably much thicker, occurs 58 feet from the bottom, and 6 miles southeast along the strike a bed 2 feet thick occurs 54 feet from the bottom, and is followed 10 inches higher by 14 inches of phosphatic shale. About 150 feet higher a 5-foot bed of gray phosphatic limestone is present in Big Popo Agie Canyon, and 6 miles southeast along the strike a 5-foot bed occurs at the same horizon. This is the bed that Blackwelder describes as occurring 12 miles west of Lander—"Brownish-gray oölitic and nodular phosphate rock full of *Productus subhorridus* and other fossils (42.4 per cent tricalcium phosphate)"[1]—4 feet 7 inches thick. This bed is readily distinguished from the lowest bed by its fauna. It contains *Producti*, spirifers, and *Spiriferina pulchra* in abundance, while the lower bed contains none of these.

The Embar limestone is well exposed in Little Popo Agie Canyon and the following description was worked out in 1913:

32. Greenish sandy shales and limestones: covered with talus and with a bed outcropping here and there	75′ to 100′	
31. Light-gray, highly siliceous limestone with the silica in druses as quartz and not as chert; this is the limestone that forms long dip slopes on the east side of the Wind River Mountains	29′	3″
30. Light-gray, cherty limestone	10′	2″
29. Dark phosphate		4″
28. Gray, cherty limestone	5′	7″
27. Dark-gray phosphate speckled with white		7″
26. Green shale		8″
25. Phosphate, black to dark-gray		3″
24. Dark-gray, siliceous limestone	3′	..

[1] Eliot Blackwelder, "Reconnaisance of the Phosphate Deposits in Western Wyoming," *U.S. Geol. Surv., Bull. 470*, p. 477.

23. Phosphate like No. 25		1″
22. Limestone like No. 24		10″
21. Phosphate like No. 25		3″
20. Gray, cherty limestone	3′	2″
19. Shale, drak-gray to bluish-gray, calcareous, somewhat nodular	23′	..
18. Dark phosphate with thin layers of gray phosphate	2′	6″

In another place the details of this bed (No. 18) were as follows:

Phosphate	8″
Yellow limestone	4″
Phosphate	2″
Yellow limestone	8″
Phosphate	4″
Yellow limestone	4″

17. Light gray, compact limestone, glauconitic in places	4′	..
16. Greenish, sandy shale, covered but near the surface (the talus was removed in places with picks in order to examine the rocks)	12′	..
15. Light-gray, compact, even-textured limestone	20′	..
14. Like No. 16	29′	..
13. Light-gray, coarse-grained, compact, thin-bedded limestone	3′	6″
12. Covered, but the rock in place within a few inches of the surface; seems to be of greenish and yellowish shale	73′	..
11. Light-purple, very compact limestone	1′	..
10. Light-gray, compact limestone	14′	..
9. Light-bluish-gray, friable limestone containing many nodules of calcite	2′	9″
8. Light-gray rock composed largely of chert nodules	1′	..
7. Light-gray, compact limestone; fragments of fossils abundant, and in some places these have been dissolved out, leaving the rock porous; *Orbiculoidea utahensis* abundant	1′	6″
6. Light-gray, cherty limestone crowded with small geodes with calcite interiors	5′	..
5. Dark-gray to black phosphate packed with *Orbiculoidea utahensis;* this is the horizon of the fish teeth, but they are rare along the Little Popo Agie	3′	6″
4. Light-gray, compact limestone containing many bryozoans and crinoid stems	1′	..
2. Light-gray limestone, in some places almost all chert; usually stands in vertical cliffs	11′	..
1. Cherty, in some places nodular, thin-bedded, closely-jointed, light to dark-gray limestone; mostly covered	14′	..
Total	375′	11″

The Tensleep contact is assumed to be at the top of a few feet of thin-bedded sandstone.

The phosphate exposures are in vertical cliffs and could not be better. Nos. 20 to 29 probably represent the upper phosphate bed in the Big Popo Agie Canyon region. The rocks above the lowest phosphate horizon contain few fossils and cannot be correlated by means of them.

The rock in which the fish remains occur is a sort of coquina, made up, for the most part, of pedicle valves of *Orbiculoidea utahensis* (I have seen only one brachial valve). Remains of many small pelecypods and gastropods are common. Just below the phosphate there is a silicified coquina made up almost entirely of pelecypod shells so closely packed that it is almost impossible to get out a good one.

The fish fauna contain six species that also occur in the Upper Coal Measures of the Mississippi Valley and one species that is known only from the Middle Carboniferous (Moscowian) of Samara, Russia. Stuckenberg[1] figures it as "genus et sp. indeter.," but gives no description, and the writer had described it as a new genus before seeing his paper. The genus is so widely different from any other that its presence in the two regions is significant for correlation purposes. One species, *Cladodus occidentalis*, occurs in the Embar, the Upper Coal Measures of the Mississippi Valley, and the Moscowian.

The invertebrates in the fauna are mainly gastropods and pelecypods and are poorly preserved. Most of the identifications are uncertain, but nearly all the specimens may be referred to species that occur in the Coal Measures of the Mississippi Valley.

DESCRIPTIONS OF SPECIES OF EMBAR FISHES

Helodus subpolitus n. sp. (Pl. I, Figs. 6–16)

The teeth of this species resemble those of *Helodus politus* so closely that they are not distinguishable in every case, but the differences are constant enough to warrant recognition.

The teeth are of various forms and sizes, generally oblong and with rounded or quadrangular ends, and slightly arched in both direc-

[1] A. Stuckenberg, "Die Fauna der obercarbonischen Suites des Wolgadurchbruches bei Samara," *Memoires du Comité Géologique*, Nouvelle Série, Livraison 23, 1905.

tions. The crown is smooth but shows a tendency to become convoluted in old age; the surface is finely and evenly punctate. Convex lateral margins terminate in a rounded edge with incipient crenulations in old forms. The concave edge is vertical and has evenly spaced crenulations on the lower half. The smaller teeth are more strongly arched in both directions than the larger.

This species differs from *Helodus politus* in having the crenulations on the sides of the teeth evenly spaced, while they are generally unevenly spaced in the latter form; they are regular in size in this form, but irregular in *H. politus;* of almost uniform width from top to bottom, but thicker at the bottom in *H. politus;* they are longer than in *H. politus*. The crenulations are generally on a retreating edge, while those of *H. politus* are on a protruding edge. *H. politus* teeth have a tendency to form a marked projection, almost a boss, in the middle of the tooth, while this is only rarely present in *H. subpolitus*. *H. subpolitus* becomes convoluted in old age; this is not true of *H. politus*.

These teeth are the most abundant in the Embar formation but their vertical range was not found to be more than 4 feet. More than 300 specimens are in the paleontological collection of the University of Missouri.

Helodus rugosus N. and W. (Pl. II, Fig. 20)

1870. *Helodus rugosus* N. and W., *Geol. Surv. Ill.*, IV, 359, Pl. II, Fig. 10.
1889. *Helodus rugosus* Woodward, *Catalogue of Fossil Fishes in the British Museum*, Part I, p. 227.
1903. *Helodus rugosus* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, 182–83, Pl. 2, Fig. 14.

One Embar specimen agrees with the original description of this form, though the peculiar surface marking is indistinct.

Crassidonta stuckenbergi gen. and sp. new (Pl. I, Figs. 17–27)

The main part of the tooth is a short, symmetrical, rounded ridge with its long axis in the line of the long axis of the tooth, and flanked on either side by narrow, thickened, winglike extensions. The ridge makes up two-thirds of the height of the tooth and one-half of the width. Its sides are steep and the top is gently rounded transversely and arched longitudinally. Near one end the longitudinal arching is sharply increased. The crowns of the smaller

teeth are smooth, but in older forms incipient, transverse wrinkling appears, and is more prominent on the wings. The ends of the central ridge project beyond the base. The base is a rhomboid with obtuse angles of slightly more than 100 degrees. The wings project downward and give to the bottom of the teeth a trough-like appearance, with the trough slightly deeper in the middle. In the largest specimen the greatest thickness is about 15 mm., the greatest length 34 mm., and the greatest width 28 mm. The average size is considerably smaller. The crown surface is closely and evenly punctate with subcircular punctations.

Co-types of it are 31 specimens from the Popo Agie and Bull Lake regions. It is No. 703 of the paleontological collection of the University of Missouri. About 25 other fragments of teeth are in the collection. Owing to the thickness of the teeth they are usually well preserved.

The foregoing description was written before the writer had seen Professor Stuckenberg's paper, "Die Fauna der obercarbonischen Suites des Wolgadurchbruches bei Samara,"[1] in which he figures the same species but lists it as "genus et sp. indeter.," and does not describe it. Stuckenberg's figures are reproduced in Pl. I, Figs. 22–24.

Campodus corrugatus Newberry and Worthen (Pl. III, Figs. 1–6)

1870. *Orodus corrugatus* N. and W., *Pal. Ill.*, IV, 358, Pl. III, Figs. 18 and 18a.
1875. *Agassizodus corrugatus* St. J. and W., *ibid.*, VI, 323–24, Pl. VIII, Fig. 24.
1879. *Chiastodus obvallatus* Trautschold, *Nouv. Mem. Soc. Imp. Natur. Moscou.*, XIV, 156–57, Pl. XVIII, Figs. 19a–d.
1889. *Campodus corrugatus* Woodward, *Cat. of Fossil Fishes*, Part I, p. 239.
1902. *Campodus corrugatus* Eastman, *American Naturalist*, XXXVI, 853–54, Fig. 2.

Trautschold's figures of *Chiastodus obvallatus* from the Moscowian of Russia are reproduced in Plate III for comparison with a specimen from above coal No. 5 at Galatea, Illinois, and the differences seem too small to recognize as specific. The Russian specimen has deeper lateral lobations than the one figured, but a specimen in the Walker Museum of the University of Chicago has lobations of about equal depth. The surface ridges appear more

[1] *Mémoires du Comité Géologique*, Nouvelle Série, Livraison 23, 1905.

pronounced in two of the drawings of the Russian specimen, but the third drawing of the same tooth places less emphasis on this character.

Campodus corrugatus has been reported from both the Upper and the Lower Pennsylvanian, but the identifications are uncertain. Those identified from the Lower Pennsylvanian are all from the lateral series of teeth and those from the Upper are from the median series.

This species is not known to be present in the Embar, but is listed here to show the relationship of Mississippi Valley strata, of the same age as the Embar, with the Moscowian of Russia.

Campodus sp. undet. (Pl. II, Figs. 21 and 21a)

A small tooth from the Embar may belong to *Campodus variabilis* N. and W. It differs from the figured forms of the lateral series in being narrower and having more numerous and more regular ridges crossing the top, but *C. variabilis* is highly variable in this respect.

It is of interest to note that *Campodus variabilis* seems to occur in the Moscowian at Gshel, Russia. Trautschold described as *Arpagodus rectangulus*[1] a form that cannot be distinguished from teeth of the lateral series as figured by St. John and Worthen.[2]

Cochliodont gen. and sp. not determined (Pl. IV, Fig. 8)

Two fragments that seem to represent the outer ends of teeth of a large cochliodont cannot be referred to any genus. They may belong to a described genus, but are too fragmentary for reference. The tooth thins and narrows toward the outer end, but does not twist, as is the case with most cochliodonts.

Janassa unguiformis St. J. and W. (Pl. II, Figs. 1–4)

1870. *Pelodus unguiformis* N. and W., *Geol. Surv. Ill.*, IV, 362–63, Pl. II, Figs. 7 and 7a.

1889. *Janassa unguiformis* Woodward, *Catalogue of Fossil Fishes in the British Museum*, Part I, p. 39.

One specimen from the Embar appears to belong to this species, and a specimen from the Upper Pennsylvanian of Missouri is also

[1] Trautschold, *Nouv. Mem. Soc. Imp. Natur. Moscou.*, Vol. XIV, Pl. XVII, Figs. 12a–d.

[2] St. John and Worthen, *Pal. Ill.*, Vol. VI, Pl. VIII, Figs. 1–22.

referred to it. They are much larger than the type, but appear to agree with it in every other respect. The present location of the type was not ascertained.

Janassa unguicula Eastman (Pl. II, Figs. 7–18)

1903. *Janassa unguicula* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, 173–74, Pl. II, Fig. 13.

1903. *Janassa unguicula* Woodruff, *Nebr. Geol. Surv.*, Vol. II, Part II, p. 288, Pl. XVIII, Fig. 8.

Classed together under this species are 25 teeth that would probably be referred to two genera and four species if they were isolated. Fig. 7 of Pl. II stands at one end of this series and Figs. 8 and 9 at the other end, and the series arranged to show small variations would be Figs. 7, 17, 16, 14, 12, 10, 9, and 15.

All of the teeth have part of the root missing but the one shown in Figs. 13 and 14 is nearly complete. The teeth range in width from 11 mm. to 19 mm., and one imperfect tooth seems to have been 25 mm.; the length is indeterminate; the thickness at the thickest part is 2 mm. to 6 mm. In every specimen the cutting edge is more or less worn and rather dull. The edge ranges from almost straight to bilobed, with three sharp cusps, the lateral ones much larger than the other. Numerous dentine tubules run lengthwise a short distance below the surface of the tooth and turn outward almost at right angles near the surface. Near the cutting edge the surface of many of the teeth is worn or eroded until the longitudinal tubules are open, as shown in Figs. 7, 10, 14, and 17, and on the rest of the surface the vertical tubules open, giving a finely punctate appearance. Teeth that are unworn are not punctate at the surface.

Three teeth have small longitudinal ridges on the posterior face, as shown in Fig. 8, but as some that agree with these in other respects lack the ridges their presence is not considered of much value in classification.

The anterior surface of the parts preserved is strongly and regularly convex and the posterior face regularly but much less strongly concave. The mark of the overlapping tooth appears on almost every specimen and is shown in nearly all of the figures. Fig. 10 shows overlap to near the cutting edge, while Fig. 17 has

much less overlap. The shape of the overlapping tooth is rarely the same as that of the tooth which it overlaps, and it is significant that none of the overlapping teeth are lobed. Fig. 10 lay next to a much narrower tooth, while all of the rest were overlapped by teeth of almost their own size.

This series indicates that some genera and several species of this type of teeth will probably prove to be invalid when more specimens are known. Eastman[1] says that the chief characteristic distinguishing this genus (*Fissodus*) from *Janassa* is that the trenchant margin is cleft or divided into two or three broad acuminate points; but that characteristic seems not to be of specific value in this case.

The type of *Janassa unguicula* would be like the tooth shown in Fig. 14, if the slight lobation of the latter were not present, and it is like that shown in Fig. 15, but the latter is a worn tooth, while the type is not worn. The type is not as thick and strong as the Embar teeth.

A specimen from Nebraska that Eastman refers to, *Fissodus inaequalis* St. J. and W., has the cutting end almost exactly duplicated in four specimens from the Embar, one of which is shown in Fig. 7 of Pl. II. This specimen is not preserved to the region where the posteriorly curved folds occur on the Nebraska form, and they were probably not present in the Embar tooth, as they do not appear on other teeth that have that part preserved.

The Carlinville, Illinois, specimen (Fig. 18 of Pl. II) is much thinner than those from the Embar but otherwise agrees with them.

Janassa angularis n. sp. (Pl. II, Figs. 5 and 6)

The type specimen of this species is incomplete but presents some marked peculiarities. From the cutting edge, which is 17 mm. wide, the tooth narrows gradually toward the other end, but only 14 mm. of the length is preserved and the condition at the missing end is not known. The cutting end is sharply curved and much worn. It seems to have been lobed originally, but wear has reduced the projecting points to the level of the bottom of the lobe. On the convex surface, 7 mm. from the edge, a shallow groove

[1] *Bull. Mus. Comp. Zoöl.*, XXXIX, 174.

less than 4 mm. wide and bounded on either side by a sharp crested ridge runs toward the narrow end. The lateral edges are sharp. Six to ten narrow grooves run parallel with the margins on each side of the tooth, beginning 11 mm. from the outer end, extending outward for 7 mm., and bifurcating and becoming obsolete in passing outward. Next to the lateral margins close-set grooves that pass backward and outward intersect the longitudinal grooves at an angle of about 45°. The concave surface of the tooth is marked with close-set longitudinal grooves formed by the etching of the surface, and opening the longitudinal pores.

Deltodus mercurii Newberry (Pl. V, Figs. 1–11; Pl. II, Figs. 27 and 28; Pl. VI, Figs. 1–6)

1876. *Deltodus mercurii* Newberry, J. N. Macomb, *Rept. Exp. Exped. from Santa Fe, N.M., to the Junction of the Grand and Green Rivers of the Great Colorado of the West*, p. 137, Pl. 3, Figs. 1, 1a.

1883. *Deltodus powellii* St. J. and W., *Geol. Surv. Ill.*, Vol. VII, 154–56, Pl. IX, Figs. 1a–f.

1883. *Deltodus mercurii* St. J. and W., *Geol. Surv. Ill.*, Vol. VII, Pl. X, Figs. 2a–d.

1883. *Deltodus propinquus* St. J. and W., *Geol. Surv. Ill.*, VII, 156–58, Pl. X, Figs. 4a–e (not Figs. 3a–e).

1889. *Deltodus mercurii*, *Deltodus powellii*, and *Deltodus propinquus* A. S. Woodward, *Catalogue of the Fossil Fishes in the British Museum*, Part I, pp. 200–201.

Newberry described *Deltodus mercurii* from one imperfect specimen and St. John and Worthen described *Deltodus propinquus* from three specimens. The following descriptions are based on a large series, though only a few teeth are nearly perfect. Some specimens from the Embar agree with the figures of *D. powellii*, others in the same series agree with the mandibular teeth described as *D. propinquus*, and others with *D. mercurii*. St. John and Worthen suggested[1] that a large series might show these forms to be conspecific.

The maxillary teeth are large, of medium width compared to the length; the posterior margin is strongly arched, with an angle between the outer and inner ends of the crown of about 147°; the anterior margin is almost straight. The inner end of the tooth is

[1] *Op. cit.*, p. 158.

thick, thinning rapidly outward from the summit of the arch on the posterior edge, and not quite so abruptly about the middle of the anterior edge. The anterior edge is turned downward at the outer end, giving to the end a twisted appearance, without causing it to be greatly recurved. A broad depression runs from the outer end to the inner at about the middle of the tooth. At the outer end this depression is very shallow and has no well-defined bounding ridge in front. The entire coronal surface is marked by rather strong, subequally spaced, transverse undulations, three to six of which are unusually deep in front of the top of the arch. In most specimens wear has reduced the surface until the deep undulations are the only ones remaining, and in some specimens the undulations seem never to have been very pronounced.

No tooth from the Embar agrees perfectly with the figures and descriptions of the type of *D. propinquus*, but the similarity is striking. Unfortunately the type of maxillary tooth of this species could not be found and the identifications had to be made entirely from figures and descriptions. *D. mercurii* and *D. powellii* were described from mandibular teeth only.

The mandibular teeth are broad and short, thick at the broad end and thinning rapidly toward the narrow end; they are strongly arched longitudinally along the anterior edge but gently curved to nearly straight along the posterior edge; the narrow end is curved to form a semicircle, but this is preserved in only one specimen. The teeth are divided into anterior and posterior parts by a furrow that runs from the outer to the inner end at about one-third of the width from the posterior edge. The furrow is broad and shallow at the outer end and narrows to a deep groove near the inner end. The part in front of the furrow is much elevated, and in the middle is crossed by two to four transverse grooves that often become deep pits on the front edge of the furrow and do not cross the hinder ridge. The outer end has no hinder ridge, but back of the middle a ridge becomes prominent and a sharp narrow part of it borders the furrow. The most perfect teeth show the origin of this posterior ridge. Originally it seems to have been a thin, flat, winglike expansion, which later doubled back on itself for 1 cm. and crumpled up at the place where the fold occurred. In some

specimens the upper part lies on the lower without having become cemented to it, while in others the evidence of folding is lacking. Behind this ridge there is, in some cases, a short, shallow, longitudinal depression. The entire coronal surface is marked by subequally spaced transverse undulations that are often indistinct.

The foregoing description refers to the large teeth. The smaller teeth lack the conspicuous posterior ridge and the strong transverse undulations, and the longitudinal furrow is less pronounced.

Fig. 10 of Pl. V shows the undulations very well, but no good specimen shows them distinctly enough over the entire surface to permit of their being brought out in a photograph, though they are readily traceable on the teeth themselves. The presence of the strong undulations suggests the formation of the large teeth by the union of several smaller teeth, but the older teeth have much the stronger undulations, unless they are reduced by wear, and the small teeth are nearly smooth.

Comparison with the type of the maxillary tooth, which is preserved in the Illinois State Museum, discloses some differences. The Wyoming teeth are larger and thicker compared to other dimensions. The Illinois specimen has subequal longitudinal ridges which are lacking in the Wyoming form. The surface of the Illinois form is marked by a sort of reticulate, threadlike network which is not present in the Wyoming specimens; but there is only one specimen of the Illinois form and there are many of the Wyoming. Specimens no larger than the type are in the collection, but they are proportionately thicker. Some specimens show irregular and discontinuous longitudinal ridges. The network on the Illinois specimen is preserved where the tooth is not worn, and all of the Wyoming specimens are worn.

I am inclined to think that the Wyoming maxillary teeth are not specifically identical with the Illinois form, and I also think that St. John and Worthen's types of mandibular and maxillary teeth from Illinois are not conspecific. The Wyoming and Illinois mandibular teeth seem to belong to the same species.

Comparison with the type of *D. mercurii* discloses very close agreement. The transverse grooves are inconspicuous on account of wear and the small size of the specimens, but the location of the grooves is easily made out.

Associated with the other specimens are forms of the following description that belong with the lower teeth. The teeth are long, slender, and narrow gradually toward the strongly arched inner end. The inner end forms a 35° arc of a circle 11 cm. in diameter; the outer end forms a 90° arc of a circle 35 mm. in diameter. The tooth is thick along the hinder margin to near the outer end, and thin along the front margin to near the outer end, where it sometimes becomes knifelike. A high, rounded ridge with a narrow top forms the greater part of the tooth. From the top of the ridge the surface slopes steeply to the back margin and almost as steeply toward the front, where the slope becomes gentle and the edge is slightly upturned. The surface is marked by undulations of the same type as on the maxillary teeth, but these are often indistinct. The surface punctation is fine. Only a few of the teeth show strong wear, and this is at the top of the arch and toward the front end.

These teeth were compared with the fragment described by St. John and Worthen and agree with it in every way, except that they are more massive.

The most striking peculiarity of *Deltodus mercurii* is the strong, subequally spaced, transverse undulations, but in many specimens these are inconspicuous or absent.

Trautschold[1] figures and describes as *Poecilodus grandis* part of a tooth that probably belongs to *Deltodus mercurii*.

The restoration.—The *Deltodus mercurii* teeth from the Embar all come from the same horizon, and there appears to be no other species of Deltodus associated with them. They thus afford a chance for determining their arrangement in the jaws. The teeth figured in Pl. V, Figs. 3 and 5, were found in the matrix within 6 inches of each other, and they fit perfectly as upper and lower dental plates. As shown in Pl. V, Figs. 2 and 4, the mandibular teeth are much more strongly curved than the maxillary, and the narrow teeth described above fit against them as shown in Pl. III, Figs. 1 and 3. By working a mandibular tooth against modeling clay a depression of the same kind as shown in the teeth figured is formed in the clay.

The maxillary tooth is not adapted to fit against any other teeth, and no teeth that seem to belong in the same jaw were

[1] *Nouv. Mem. Soc. Imp. Natur. Moscou.*, XIV, 149–50, Pl. XVII, Figs. 13a and b.

found. There are holodont teeth in abundance in the phosphate bed that bears *D. mercurii*, but there seems to be no way of associating them with the *Deltodus* teeth.

In 1905 the writer differentiated *Sandalodus* from *Deltodus* on the basis of the theory that the former had only one tooth to each ramus of the jaw and the latter three.[1] The present investigation indicates the correctness of the conclusion that *Sandalodus* had only one tooth in each ramus, but this was a maxillary tooth, and the *Deltodus* teeth are mandibular of the same species. One of the evidences given by Branson that *Deltodus* had three teeth to each ramus was the truncated or grooved anterior edge of the median teeth, adapted for articulation with other teeth. The restoration here given shows the median teeth articulating with each other and dispenses with the probability that there was a third tooth in each ramus. It is probable that the dentition of forms described from the Mississippian of the interior may be reconstructed, and the writer intends to attempt such reconstruction.

The restoration presented in Pl. VI, Figs. 1–3, is the result of the study of a large series of teeth and is believed to be approximately correct.

The right maxillary tooth is modeled and the left is perfect. The right outer mandibular has the outer end restored and the left inner mandibular is restored at the outer end. The extent of restoration is easily determined in the photograph. Fig. 1, showing the upper and lower dentition apposed, probably represents the back end of the jaws, and the teeth were probably deeply inserted.

Cladodus occidentalis Leidy (Pl. II, Figs. 23 and 24)

1859. *Cladodus occidentalis* Leidy, *Proc. Acad. Nat. Sci. Phila.*, p. 3.
1866. *Cladodus mortifer* Newberry and Worthen, *Geol. Surv. Ill.*, II, 22, Pl. I, Fig. 5.
1870. *Cladodus mortifer* St. John, *Proc. Am. Phil. Soc.*, XI, 431.
1872. *Cladodus mortifer* St. John, *Final Rept. U.S. Geol. Surv. Nebr.*, p. 239, Pl. III, Fig. 6; Pl. VI, Fig. 13.
1873. *Cladodus occidentalis* Leidy, *Rept. U.S. Geol. Surv. Territ.*, I, 311, Pl. XVII, Figs. 4–6.
1897. *Cladodus mortifer* Newberry, *Trans. N.Y. Acad. Sci.*, XVI, 285, Pl. XXII, Fig. 2.
1903. *Cladodus occidentalis* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, 168, Pl. II, Figs. 3, 8, and 9.

[1] E. B. Branson, *Jour. Geol.*, XIII, 26.

Four imperfect specimens and several fragments of this species were collected. They agree with St. John's excellent description of 1872 except in two minor details. The striae on the main cone project nearly to the summit instead of only half-way. St. John does not figure any specimens with the summit of the cone preserved, and this part of the description probably came from Newberry and Worthen's description of *Cladodus mortifer*. The lateral denticles do not have sharp cutting edges except as these are formed by one more prominent ridge on each side.

This species has been reported from the Upper Coal Measures near Springfield, Illinois, southwestern Iowa, Manhattan, Kansas, Nebraska City and Table Rock, Nebraska, and from the Coal Measures of Indiana and the Permo-Carboniferous of Roca, Nebraska.

Trautschold[1] identified a form from the Moscowian as *Cladodus lamnoides* Newberry and Worthen, but his figures and descriptions indicate *C. occidentalis*, and, as other species are common to the Moscowian and the Upper Pennsylvanian of the Mississippi Valley, this is probably the correct reference.

ICHTHYODORULITES

Ctenacanthus browni n. sp. (Pl. IV, Fig. 7, and Text-Fig. 6)

The holotype is an imperfect spine. The part preserved is 13 cm. long, 2 cm. wide at the outer end, and 27 mm. wide at the inner. None of the inserted portion is retained. The curvature is very slight. The pulp cavity at the outer end is 7 mm. by 2 mm., and at the inner end 11 mm. by 4 mm. The surface is ornamented by 20 to 23 longitudinal, smooth, closely spaced costae that are slightly wider than the intercostal spaces and are imperfectly divided into three sets. In the anterior set there are 4 costae and 4 intercostal spaces in 5 mm., in the second there are 6 costae and 6 intercostal spaces in 5 mm., and in the third 7 or 8 in 5 mm. The costae in the first set are high and narrow, in the second set narrower and about half as high, and in the third of about the same width as in the second, but very low and becoming obsolete at the back. The posterior face of the spine is slightly excavated, contains closely

[1] "Die Kalkbruche von Mjatschkowa: Eine Monographie des obern Bergkalks," *Nouv. Mem. Soc. Imp. Natur. Moscou*, XIII, 10–12, Table I, Figs. 3a–e.

spaced, linear markings, and has lateral margins, with denticles obscure or lacking. The anterior face is marked by a high, thin, almost knifelike ridge.

This species is named for N. H. Brown, who collected the first fishes from the Embar and who has rendered many valuable services to geologists working in the Lander region.

Ctenacanthus obscuracostatus n. sp. (Pl. IV, Fig. 2, and Text-Figs 2 and 3)

This imperfect spine differs from that last described in that the ribs are much finer and lower, in that they change gradually from coarser behind to finer in front, and in that the spine narrows to a knifelike edge in front. It agrees with the other spine in the absence or obscurity of ornamentation.

The length of the part preserved is 165 mm., the width 27 mm. at the outer end and 41 mm. at the inner. It was inclined backward at a sharp angle. A large part of the inserted end is missing, but in the part preserved the pulp cavity is open at the back for more than 6 cm. The cavity is shown at the outer and inner ends of the spine in Figs. 2 and 3.

Ctenacanthus amblyxiphias Cope (Pl. II, Fig. 25, and Text-Fig. 5)

1891. *Ctenacanthus amblyxiphias* Cope, *Proc. U.S. Nat. Mus.*, XIV, 449, Pl. XXVII, Fig. 3.

1903. *Ctenacanthus amblyxiphias* Eastman, *Bull. Mus. Comp. Zoöl.*, XXXIX, Pl. 2, Figs. 22 and 23.

1903. *Ctenacanthus amblyxiphias* Woodruff, *Geol. Surv. Nebr.*, II, Part II, 288, Pl. XVIII, Fig. 5.

1911. *Ctenacanthus amblyxiphias* Hussakof, "Revision of the Amphibia and Fishes of the Permian of North America," *Carnegie Institution Publication No. 146*, pp. 161–62, Pl. 30, Figs. 6 and 6a.

This fragment is referred provisionally to Cope's species though it does not agree with his description in these respects: that the ribs do not become smaller posteriorly so as to be of half the diameter of the anterior ribs and that there are no tubercles on the posterior margins. Most of the ornamentation has weathered off, but that preserved agrees with Eastman's figures and not with Cope's.

Eastman makes definite reference to the locality and formation from which the specimens that he figures were collected, but Cope and Hussakof give their specimens as from the Permian of Texas.

As considerable doubt has recently been expressed concerning the age of much of the so-called Permian of Texas, it is not safe to give the range of this species as extending into the Permian without more specific data.

Eunemacanthus keytei n. sp. (Pl. IV, Fig. 1, and Text-Fig. 1)

The preserved part of this spine is only 35 mm. in length but includes parts of both exserted and inserted portions. The pulp cavity is small and completely inclosed. The front of the spine is formed of one rounded enameled ridge. Next to the inserted

FIGS. 1–6.—(1) Cross-section of spine of *Eunemacanthus keytei* Branson; (2) cross-section of spine of *Ctenacanthus obscuracostatus* Branson, at base of preserved part; (3) cross-section of spine of *Ctenacanthus obscuracostatus* Branson, at outer end of preserved part; (4) cross-section of spine of *Batacanthus gigas* Branson, at outer end of preserved part; (5) cross-section of spine of *Ctenacanthus amblyxiphias* Cope; (6) cross-section of spine of *Ctenacanthus browni* Branson.

part, one side has 9 broad, flat-topped ribs, and the other 8 such ribs. The space between the ribs is narrower than the ribs, flat-bottomed, and marked with longitudinal striae formed by the outcropping of longitudinal pores. The ribs increase downward by bifurcation and probably by implanation. The back of the spine is convex and is marked by about 25 striae formed in the same way as those between the ribs. The spine tapers rapidly and the exserted part seems to have been about 10 cm. long.

This form differs from *E. costatus* N. and W.[1] in tapering more rapidly and in the convexity of the back.

The species is named for I. Allen Keyte, of Colorado Springs, Colorado, whose untiring zeal in collecting added many specimens to the cabinets of the University of Missouri.

[1] *Geol. Surv. Ill.*, VII, Pl. XXIII, Fig. 2.

Batacanthus gigas n. sp. (Pl. IV, Figs. 3–6, and Text-Fig. 4)

The holotype is a spine with outer and inner ends missing. The part preserved is 26 cm. long, 41 mm. wide at the outer end, and about 65 mm. wide at the inner. If the rate of tapering did not change in the missing parts, about 18 cm. are gone from the outer end and about 8 cm. from the inner. The spine is much compressed, narrowly oval in outline, without flattening on the back edge and with only an indication of an angle on the front. It is so poorly preserved that the ornamentation over most of the surface cannot be made out. Sharp-topped, ribbed denticles lie in close-set rows parallel to the front edge, and the presence of a few elongated, low denticles, set diagonally near the front edge, suggests a type of ornamentation like that in *Xystracanthus mirabilis* St. John and Worthen.[1]

The preservation does not permit of the determination of the angle of insertion of the inner end. The pulp cavity is not large at the inserted end and is open at the back for about 12 cm. After becoming closed it takes its course near the back of the spine.

This species may be recognized by its large size, oval shape, and ornamentation.

Spine denticles of an Elasmobranch (Pl. II, Fig. 26)

Isolated specimens of little, cone-shaped denticles shown in this figure are abundant wherever the lowest phosphate bed was examined and several specimens with a number of associated denticles are in the collection, but they have not been found attached to spines. In some specimens three layers of denticles occur and the individuals of the overlying layers alternate with those of the underlying. The denticles are smooth, semicircular to hexagonal in outline, irregular in size, have thin walls, and are strongly concave from below.

VALUE OF PALEOZOIC FISHES IN CORRELATING STRATA

Fish remains have been used very little in exact correlation of formations, but they should be of high value for such purposes. As fishes swim freely and as few have their habitat determined by

[1] *Geol. Surv. Ill.*, VI, Pl. XX, Fig. 1.

depth of water, most species are widely distributed. As most of them are not bottom dwellers, their remains are about as likely to be found in one kind of rock as in another. The time range of most species is small. Of 112 species of cochliodont sharks listed by Hay in his *Bibliography and Catalogue of Fossil Vertebrates*, only three have a vertical range of more than one formation and the identifications in the three cases are not always reliable. The wide distribution, independence of bottom conditions, and small vertical range make them of particular value in correlating strata. But unfortunately most fossil fishes are labeled, as the older collections of invertebrates were, as from a given locality and formation, without more specific data.

The writer has been at work for several years in trying to assemble the data on fossil fishes for use in correlation.

INVERTEBRATES FROM THE LOWER EMBAR

Orbiculoidea utahensis Meek (Pl. III, Figs. 22–25)

1877. *Discina* sp. undet. Meek, *U.S. Geol. Expl. 40th Par., Rept.*, IV, 99, Pl. 10, Fig. 3.
1877. *Discina utahensis* Meek, *ibid.*, IV, 99.
1910. *Lingulidiscina utahensis* Girty, *U.S. Geol. Surv., Bull. 436*, pp. 24–25. Pl. I, Fig. 11.
1911. *Lingulidiscina utahensis* Woodruff, *U.S. Geol. Surv., Bull. 452*, p. 13.
1911. *Lingulidiscina utahensis* Blackwelder, *U.S. Geol. Surv., Bull. 470*, p. 477.
1913. *Lingulidiscina utahensis* Blackwelder, *Am. Jour. Sci.*, 4th Ser., XXXVI, 178.

Much of the lowest phosphate bed is a sort of coquina made up, for the most part, of pedicle valves of this species. The average diameter of the shells is a little more than 2 cm. I have followed Girty in identifying this species as *O. utahensis*, but comparison with specimens from the Coal Measures of Missouri, identified as *Orbiculoidea convexa* Shumard, shows no differences of specific value. The brachial valve figured in Pl. III proves that the species is not a *Lingulidiscina*.

Plagioglypta canna White (Pl. III, Fig. 13)

This species is common and seems to be the only one that ranges from the lowest phosphate bed through the higher beds.

Nucula perumbonata White (Pl. III, Figs. 18–19)

1879. *Nucula perumbonata* White, *Bull. U.S. Geol. and Geog. Surv. Terr.*, V, 217.

1880. *Nucula perumbonata* White, *Cont. to Inv. Pal.*, No. 6, p. 136, Pl. 34, Figs. 7a–b.

The type came from Wild Band Pockets, in northern Arizona, 15 miles southward from Pipe Springs, in the Carboniferous, near the top.

The Embar specimens are abundant, but only two good ones were collected, and they came from the coquina just below the phosphate. The surface markings are not well preserved, but seem to be exactly like those of the type. The Embar specimens come from the Big Popo Agie region, S.W. $\frac{1}{4}$ S. 16, T. 32 N., R. 100 W.

Nucula pulchella Beede and Rodgers (Pl. III, Figs. 7–8)

1899. *Nucula pulchella* Beede and Rodgers, *Kan. Univ. Quart.*, VIII, 132, Pl. XXXIV, Figs. 5a–c.

1900. *Nucula pulchella* Beede and Rodgers, *Univ. Geol. Surv. Kan.*, VI, 151, Pl. XXI, Figs. 5a–c.

1909. *Nucula pulchella* Beede and Rodgers, *Univ. Geol. Surv. Kan.*, IX, 368, 380, Pl. XLII.

This species is represented as interior molds, which agree in shape and size with *N. pulchella*, but the reference is uncertain. They are found in the lower phosphate bed in Big Popo Agie Canyon, Little Popo Agie Canyon, and Bull Lake Creek Canyon, Wyoming, and in the Kickapoo limestone about the middle of the Missouri group of Kansas.

Nucula sp. (Pl. III, Figs. 20–21)

This is one of the most abundant forms occurring in the lower phosphate bed, but the specimens are all interior molds. They agree in shape and size with the forms which Meek found at Nebraska City and which he identified provisionally with *Nucula beyrichi*.[1] They also agree in shape and size with Girty's[2] *Nucula* sp. a. from the Guadalupian.

[1] Meek, *Paleontology of Eastern Nebraska*, p. 203, Pl. 10, Figs. 18 and 19a–b.

[2] Girty, *Prof. Paper 58*, p. 421, Pl. XXIV, Fig. 22.

Leda bellistriata Stevens (Pl. III, Figs. 9–12)

1898. *Nuculana bellistriata* Weller, *U.S. Geol. Surv., Bull. 153*, pp. 380–81. Synonomy to 1898.
1900. *Nuculana bellistriata* Beede, *Univ. Geol. Surv. Kan.*, VI, 148, Pl. 20, Figs. 14 and 14b.
1903. *Leda bellistriata* Girty, *U.S. Geol. Surv., Prof. Paper 63*, pp. 442–43.
1909. *Leda bellistriata* Grabau and Shimer, *North America Index Fossils*, "Invertebrates," I, 401.
1909. *Nuculana bellistriata* Beede and Rogers, *Univ. Geol. Surv. Kan.*, IX, 368, 380, Pl. XLII.

Specimens referred to this species are preserved as internal molds and the identification is uncertain. The shape and size suggest the variety *attentuata*. The length of the largest specimen is 12 mm., the length in front of the umbones 8 mm., the width 7 mm. It is found in the lower phosphate bed from Bull Lake Creek to south of the Little Popo Agie River, ranges from the bottom of the Coal Measures to the top of stage G in Kansas, and has been reported from both the Upper and Lower Coal Measures from various states in the Mississippi Valley and eastward.

Pleurophorus sp. undet. (Pl. III, Figs. 14 and 15)

This species is represented by interior molds. It is very small; the length of an average specimen is 7 mm. and the width 4 mm. It resembles *P. subcostatus* Meek and Worthen, except in size. It is common in the lowest phosphate bed from Bull Lake Creek to the Little Popo Agie River.

Euphemus carbonarius Cox

1898. *Bellerophon carbonarius* Weller, *U.S. Geol. Surv., Bull. 153*, pp. 139–40. Synonomy to 1897.
1909. *Euphemus carbonarius* Beede and Rogers, *Univ. Geol. Surv. Kan.*, IX, 369, 382.
1909. *Euphemus carbonarius* Grabau and Shimer, *North America Index Fossils*, "Invertebrates," I, 621.

This species is common in the coquina just below the phosphate, but the preservation has left the surface markings obscure and the identifications are not positive.

In the Big Popo Agie Canyon, specimens were collected for two or three miles south of the canyon. It ranges through the Upper

and Lower Coal Measures in the Mississippi Valley, and occurs in the Marshall of Michigan.

Bellerophon bellus Keyes (Pl. III, Figs. 16 and 17)

1895. *Bellerophon bellus* Keyes, *Mo. Geol. Surv.*, V (1894), 148, Pl. 50, Fig. 7. Found in the Upper Coal Measures, Kansas City, Missouri.

1899. *Patellostium nodocostatum* Girty (not Gurley), *19th Ann. Rept., U.S. Geol. Surv.*, Part 3, p. 590. Found in the Upper Coal Measures, Atoka quadrangle.

1903. *Patellostium bellum* Girty, *U.S. Geol. Surv., Prof. Paper 16*, pp. 474–75. Found in the Hermosa and Rico formation, San Juan region, Colorado.

1906. *Bellerophon bellus* Woodruff, *Geol. Surv. Nebr.*, Vol. II, Part 2, p. 282, Pl. 15, Fig. 2. Extreme upper part of the Coal Measures of Nebraska.

Only one specimen of this species was found, and it agrees in every detail with Keyes's description, though the transverse ridges are not as regular as shown in his figures. The following is the original description:

> Shell subglobose, expanding rapidly at the aperture, which is somewhat reniform, with the lip reflected at the sides. Surface marked by a rather prominent, longitudinal carina along the median portion of the shell; strong transverse ridges parallel to the lines of growth pass from one umbilical region to the other; these are crossed by less prominent longitudinal lines, the two sets forming a beautiful cancellated area.

The Embar specimen was collected in the Big Popo Agie Canyon, S.W. $\frac{1}{4}$ S. 16, T. 32 N., R. 100 W.

CONCLUSIONS

1. The abundance of cochliodont sharks, which have never been reported from strata younger than the Pennsylvanian, indicate an age older than the Permian.

2. The presence of invertebrates that are nearly all referable to species occurring in the Upper Coal Measures of the interior and of sharks that are also common to the Upper Coal Measures indicate the homotaxy of the Lower Embar of Wyoming and the Upper Coal Measures of the Mississippi Valley.

3. The presence of a peculiar genus of shark in the Moscowian of Samara, Russia, and in the Embar makes probable the correlation of these widely separated formations. This conclusion is strengthened by the presence of *Chomatodus corrugatus* in the Rus-

sian Moscowian and in the Upper Pennsylvanian of the Mississippi Valley, and *Cladodus occidentalis* in the Moscowian, the Embar, and the Mississippi Valley Upper Pennsylvanian.

Unfortunately the data for the fish remains from the Mississippi Valley are not complete enough to furnish a basis for exact correlation. The fossils are labeled, in most cases, as from the Coal Measures, Upper Coal Measures, or Lower Coal Measures, and the designations "Upper" and "Lower" are not trustworthy in all cases.

The data for the Russian specimens is not all that is to be desired. *Crassidonta stuckenbergi*, with positive identification, is from Samara, from beds correlated with the Moscowian by Stuckenberg. *Campodus corrugatus* "appears to come from the *Fusulina limestone* of Miatschkowa," the implication being that the specimen is not labeled. The identification of *Cladodus occidentalis*[1] is somewhat uncertain without comparison with American specimens.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the writer's obligations to Professor Stuart Weller for the loan of specimens and the privilege of studying the fish remains in the Walker Museum of the University of Chicago; to Dr. A. R. Crook for the loan of specimens from the Illinois State Museum; to Dr. E. H. Barbour for the loan of specimens from the University of Nebraska museum; to Dr. T. E. Savage for the loan of material from the University of Illinois; to Dr. Louis Hussakof for the loan of specimens from the American Museum; and to Mr. D. K. Greger for assistance in preparing and photographing the specimens.

EXPLANATIONS OF PLATES

PLATE I

FIGS. 1–5.—*Helodus politus* Newberry; co-types for comparison with the figures of Helodus subpolitus (collection of the University of Chicago).

FIGS. 6–16.—*Helodus subpolitus* n. sp.: Figs. 6–13, top views showing variations; Figs. 14–16, side views showing crenulations (No. 704).[2]

[1] Girty, *Prof. Papers 58*, p. 157.

[2] All specimens not otherwise designated are in the collection of the University of Missouri, and the number given is the University of Missouri museum number.

FIGS. 17–21, 25–27.—*Crassidonta stuckenbergi* n. gen. and sp.: Figs. 17, 18, 21, and 26, top views of four teeth; Fig. 19, side view; Fig. 20, end view; Figs. 25 and 27, bottom views (No. 703).

FIGS. 22–24.—Stuckenberg's figures of a specimen of *Crassidonta stuckenbergi* from the Moscowian, for comparison with the specimens from the Embar.

PLATE II

FIGS. 1–4.—*Janassa unguiformis* St. John and Worthen: Fig. 1, outer coronal face of tooth with part of inserted end missing; Fig. 2, lateral view of the same specimen; found in the Embar, Big Popo Agie Canyon, Wyoming (No. 706); Fig. 3, outer coronal face of almost perfect tooth; Fig. 4, lateral aspect of the same specimen, Upper Pennsylvanian of Missouri (No. 421). (All figures show about natural size.)

FIGS. 5 and 6.—*Janassa angularis* Branson: Fig. 5, outer coronal view of specimen with inserted end missing; Fig. 6, lateral aspect of the same specimen; found in the Embar, Bull Lake Creek, Wyoming (No. 713). (Figures show about natural size.)

FIGS. 7–19.—*Janassa unguicula* Eastman: Figs. 7, 9, 10, 12, 14, 17, outer coronal views of several teeth showing variations (inserted end of all specimens missing); Fig. 8, inner coronal view of the same tooth as Fig. 9; Fig. 11, lateral view of the same tooth as Fig. 12; Fig. 13, lateral view of the same tooth as Fig. 14; 9/10 natural size, found in the Embar, Bull Lake Creek and Big Popo Agie Canyon, Wyoming (Nos. 708 and 720); Figs. 18 and 19, lateral and outer coronal views of a tooth from Carlinville, Illinois, Upper Pennsylvanian, 16/13 natural size (No. 7056 of the Illinois State Museum).

FIG. 20.—*Helodus rugosus* Newberry and Worthen: side view of the only specimen collected from the Embar; twice natural size; the peculiar surface markings may be made out in the photograph.

FIGS. 21 and 21a.—*Campodus* sp?: top and end views of the only specimen collected from the Embar.

FIG. 22.—*Deltodus mercurii:* end view of an Embar specimen of mandibular tooth for comparison with Fig. 16, of the type; ×7/8.

FIGS. 23 and 24.—*Cladodus occidentalis* Leidy: bottom and inner views of an imperfect tooth; summit of cones restored after other specimens; ×7/8; found in the Embar, Big Popo Agie Canyon, Wyoming (No. 705).

FIG. 25.—*Ctenacanthus amblyxiphias* Cope; side view of imperfect spine from Bull Lake Creek, Wyoming, 38 feet from the bottom of the Embar; ×10/9 (No. 718).

FIG. 26.—Denticles probably coming from the spine of an Elasmobranch; ×10/9; found in the Big Popo Agie Canyon, Wyoming, Embar (No. 707).

FIGS. 27 and 28.—*Deltodus mercurii* Newberry; side and top views of an almost perfect right median mandibular tooth; ×8/9; found in the Embar, Bull Lake Creek, Wyoming (No. 716).

PLATE III

FIGS. 1–3.—*Campodus corrugatus* N. and W.: specimen figured by Trautschold as the holotype of *Chiastodus obvallatus;* ×1; found in the Moscowian of Mjatschkowa, Russia.

FIGS. 4–6.—*Campodus corrugatus* N. and W.: found in the Upper Coal Measures above coal No. 5, Galatea, Illinois; ×3/4.

FIGS. 7–8.—*Nucula pulchella* Beede and Rodgers; found in the Embar, Big Popo Agie Canyon, Wyoming; lateral views of two specimens; ×4/3 (No. 751).

FIGS. 9–12.—*Leda bellistriata* Stevens: found in the Embar, Big Popo Agie Canyon, Wyoming; Figs. 9–11, lateral views of casts; Fig. 12, hinge line of a cast; ×4/3 (No. 722).

FIG. 13.—*Plagioglypta canna* White: found in the Embar, Big Popo Agie Canyon, Wyoming; view of imperfect specimen; ×4/3 (No. 726).

FIGS. 14–15.—*Pleurophorus* sp?: found in the Embar, Big Popo Agie Canyon, Wyoming; lateral views of two nearly perfect casts; ×4/3 (No. 727).

FIGS. 16–17.—*Bellerophon bellus* Keyes: found in the Embar, Big Popo Agie Canyon, Wyoming; Fig. 16, dorsal aspect; Fig. 17, lateral aspect; ×4/3 (No. 723).

FIGS. 18–19.—*Nucula perumbonata* White: found in the Embar, Big Popo Agie Canyon, Wyoming; Fig. 18, dorsal aspect; Fig. 19, lateral aspect; ×4/3 (No. 725).

FIGS. 20–21.—*Nucula* sp?: found in the Embar, Big Popo Agie Canyon, Wyoming; Fig. 20, lateral aspect of a cast; Fig. 21, dorsal aspect of a cast; ×4/3 (No. 724).

FIGS. 22–25.—*Orbiculoidea utahensis* Meek: found in the Embar, Big Popo Agie Canyon and Little Popo Agie Canyon, Wyoming; Fig. 22, lateral view of brachial valve, ×3/2; Fig. 23, outer surface of pedicle valve, ×7/5; Fig. 24, inner surface of pedicle valve, ×3/2; Fig. 25, brachial valve; ×4/3 (No. 750).

PLATE IV

FIG. 1.—*Eunemacanthus keytei* Branson: lateral view of holotype, ×9/10; found in the Embar, Big Popo Agie Canyon, Wyoming (No. 711).

FIG. 2.—*Ctenacanthus obscuracostatus*: Branson lateral view of holotype, ×7/8; found in Big Popo Agie Canyon, Wyoming (No. 710).

FIGS. 3–6.—*Batacanthus gigas* Branson: Fig. 3, lateral view of imperfect spine, ×1/2; Figs. 4 and 5, top views of spine denticles, ×3; Fig. 6, surface ornamentation; ×2 (No. 715).

FIG. 7.—*Ctenacanthus browni* Branson: lateral view of type, ×4/5; found in Big Popo Agie Canyon, Wyoming (No. 709).

FIG. 8.—Unidentified cochliodont: top view of outer end of tooth, ×3/4; found in Big Popo Agie Canyon, Wyoming (No. 714).

PLATE V

All figures are of *Deltodus mercurii* Newberry.

FIG. 1.—Top view of median mandibular tooth with outer end missing (No. 712).

FIG. 2.—Lateral view of complete left outer mandibular tooth; ×4/5 (No. 712).

FIG. 3.—Top view of same tooth; ×9/10.

FIG. 4.—Lateral view of complete left maxillary tooth; ×4/5 (No. 712).

FIG. 5.—Top view of same tooth.

FIG. 6.—Top view of right mandibular tooth with outer end missing (No. 712).

FIG. 7.—Lateral view of mandibular tooth with outer end missing; ×5/6 (No. 716).

FIG. 8.—Top view of right outer mandibular tooth with outer end missing; ×2/3 (No. 716).

FIG. 9.—Top view of left outer mandibular tooth with outer end missing (No. 712).

FIG. 10.—Top view of right maxillary tooth restored after Fig. 5 for comparison with Fig. 4a of the type; ×3/4; markings like those on the outer end of the specimen cover the entire surface of unworn teeth (No. 716).

FIG. 11.—Side view of the tooth shown in Figs. 4 and 5.

The specimens figured as 7 and 8 are from the Bull Lake Creek region, Wyoming, and the others from the Big Popo Agie region, Wyoming.

PLATE VI

All figures are of *Deltodus mercurii* Newberry.

FIG. 1—Restoration of upper and lower dentition viewed from the rear; ×9/15.

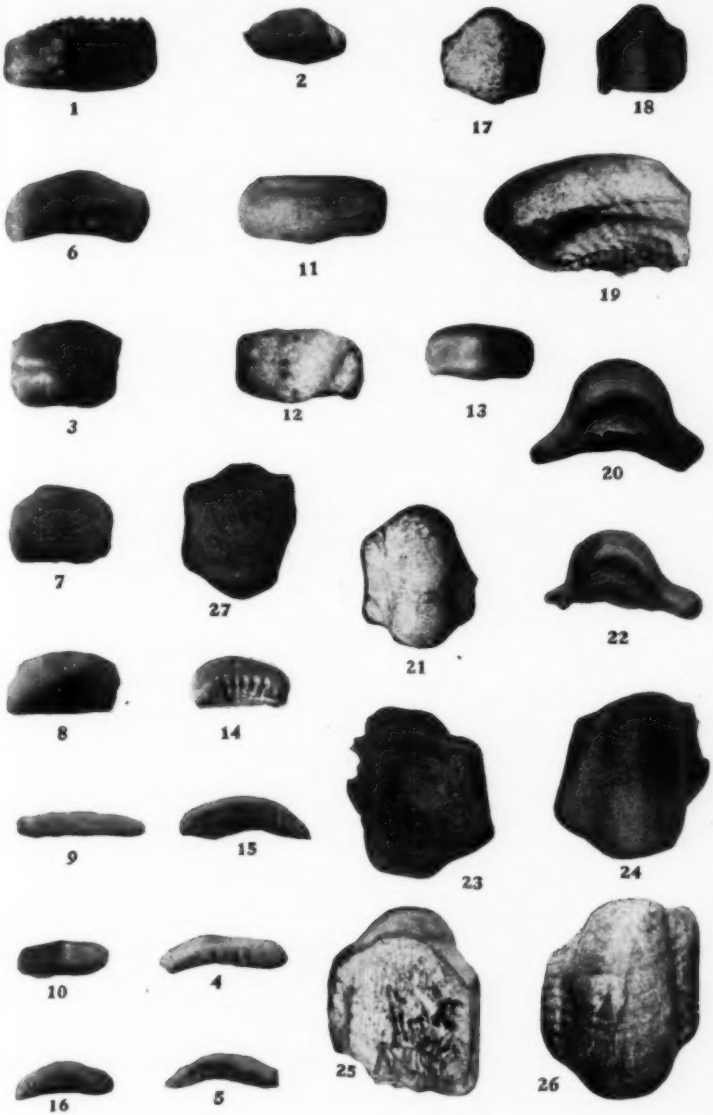
FIG. 2.—Restoration of upper dentition; right tooth restored; ×9/15.

FIG. 3.—Restoration of lower dentition; stippled area of inner tooth of left side and outer of right restored; ×5/8.

FIG. 4.—Mandibular tooth from the Embar for comparison with the type; ×13/16; restored in outline.

FIG. 5.—Side view of same tooth; ×1.

FIG. 6.—Top view of type of *Deltodus mercurii:* mandibular tooth; ×13/16; restored in outline; found in the Coal Measures, Santa Fe, New Mexico (No. 462 of the collection of the American Museum of Natural History).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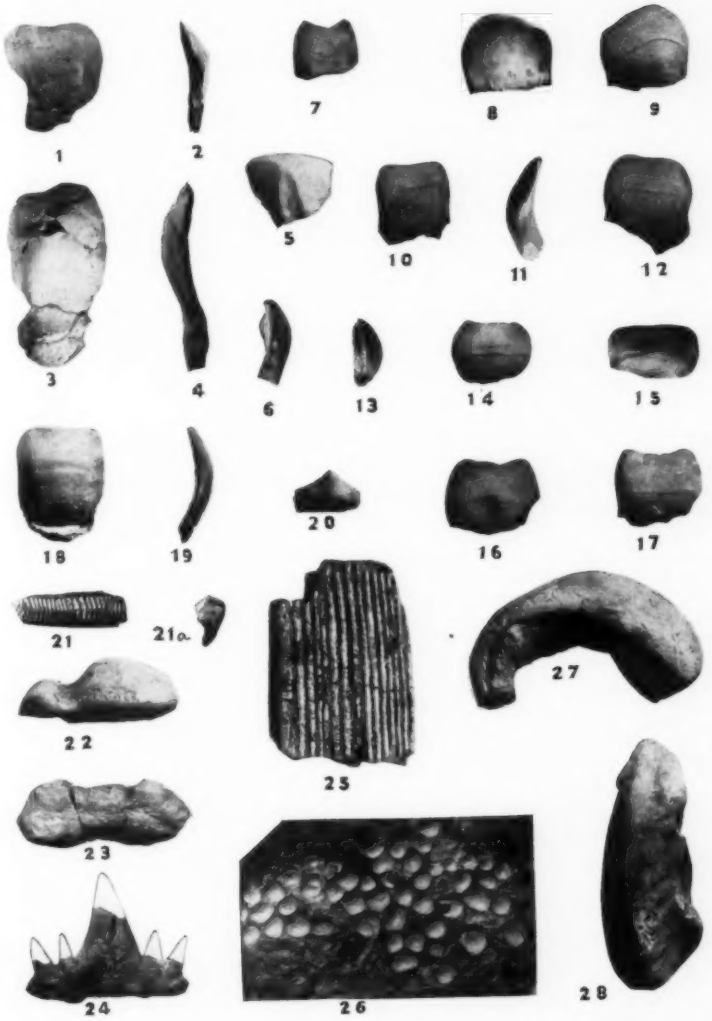
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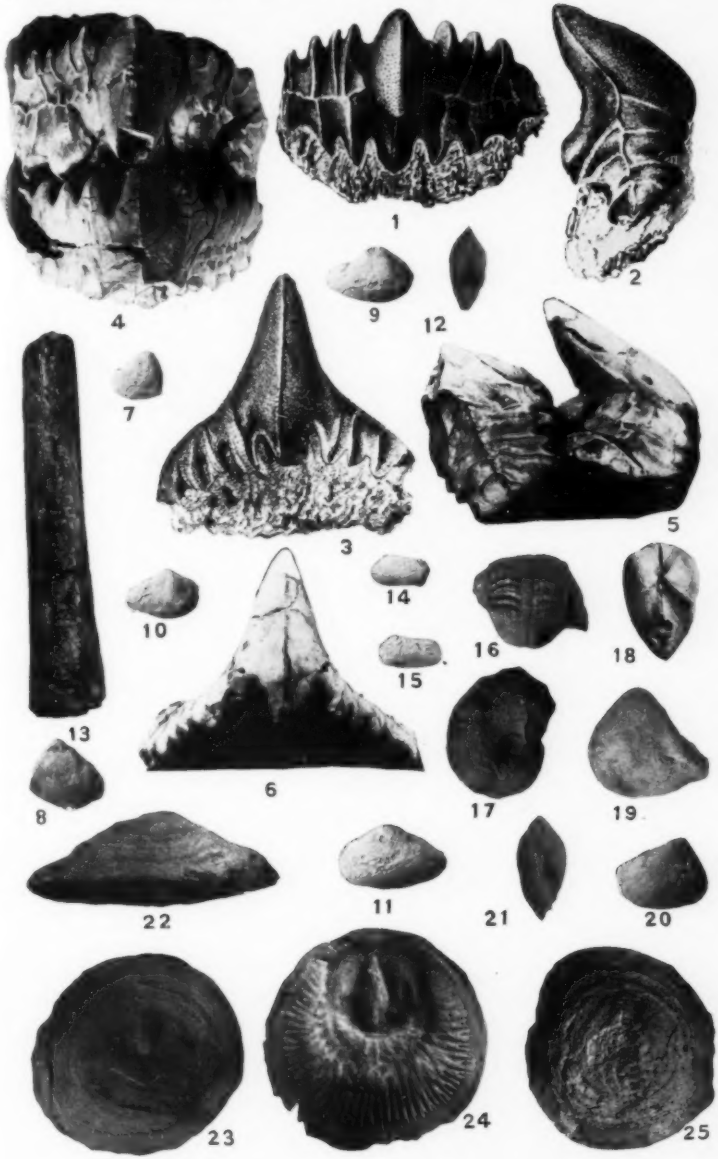
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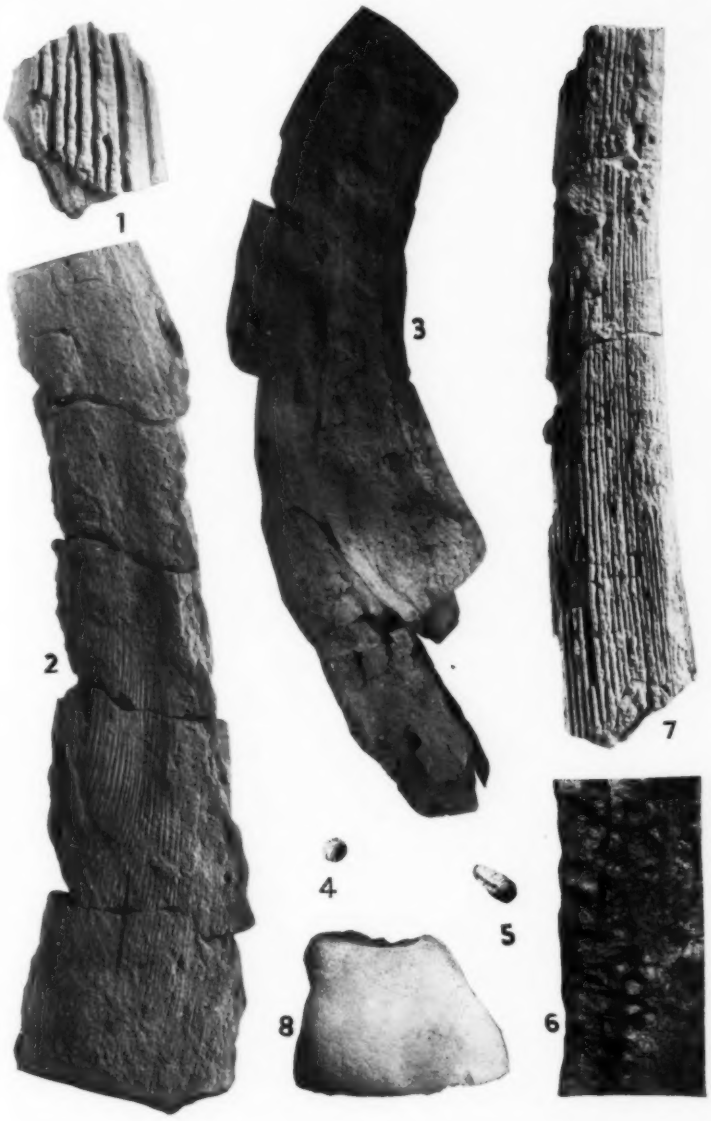
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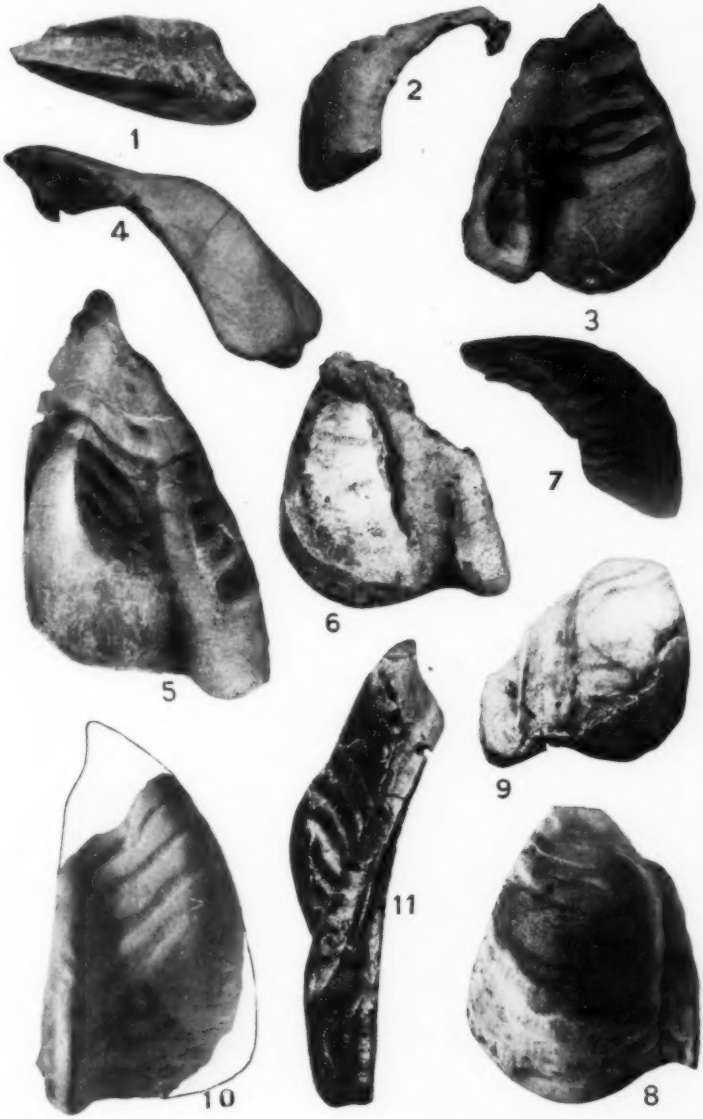
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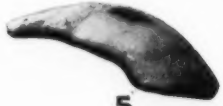

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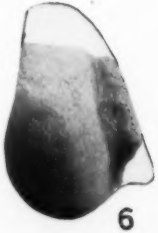

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3

EVOLUTION OF THE BASAL PLATES IN MONOCYCLIC CRINOIDEA CAMERATA

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PART III

EVOLUTION OF THE BASE IN MONOCYCLIC CAMERATA

1. EVOLUTION OF THE PENTAGONAL BASES

Having assumed that the anal plate plays no part in the evolution of the pentamerous base in the monocyclic Camerata, the succession of changes modifying this base may now be considered.

Starting with the simple pentagonal base *a—b—c—d—e—* (Fig. 9, No. 1), the first change noted is the reduction in number of basals from five to four. It is evident that this change is due to the anchylosis of but one pair of plates, either the anterior pair or occasionally in *Melocrinus* the sinistro-laterals. Accompanying this change there is usually a symmetrical reduction of the compound plate and an asymmetrical reduction of the adjacent basals. The formula for the base so developed is *a—b—cd—e—* (Fig. 9, No. 2) for the anterior anchylosis and *a—bc—d—e—* for anchylosis of the sinstro-laterals (Fig. 5, No. 2*a*). The next step is the reduction to three unequal basals by the anchylosis of two pairs of basals. In this combination the simple basal may be any one of the five primary plates, although the left- or right-anterior plate is usually the simple one. Anchylosis is here accompanied either by asymmetrical reduction of the compound plates on the side apposed to the simple basal or by deep-seated and symmetrical reduction. In either case the enlargement of the simple basal is usually symmetrical. Any of the three-basal forms might arise from any of the possible combinations of four basals, provided that the anchylosed pair in the four-basal form appears as one of the compound units in the three-basal form. Thus the four-basal form *a—b—cd—e—* might have given rise to a type in which either

of the postero-lateral basals is free, as in *ea—b—cd—*, or *ab—cd—e—* The probabilities are, however, that the three-basal forms originated directly from the five-basal forms, without an intermediate four-basal stage. This succession is shown diagrammatically by changing formula *a—b—c—d—e—* to *ab—c—de—* for the *Platycrinus* type of base and to *ea—bc—d—* for the *Hapalocrinus* type of base (Fig. 9, Nos. 1, 3, and 4). Two-basal forms are not known in this

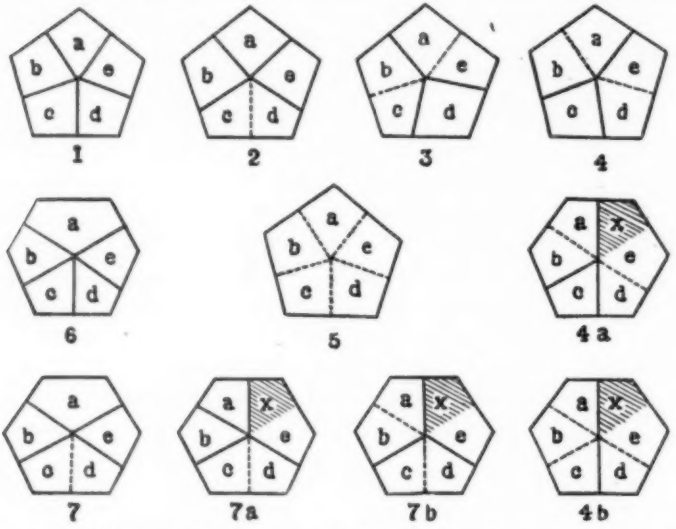

FIG. 9.—Diagrams illustrating the evolution of the base in the Camerata on the theory of atrophy and compensating hypertrophy: 1–5, combinations of the primitive five-basals; 1, 6, 7–7*b*, succession in the Batocrinidae; 1, 7*b*, succession in formation of the tripartite base in the Hexacrinidae; 1, 4–4*b*, succession in the formation of the bipartite base in the Hexacrinidae.

succession, so the next stage is that of complete anchylosis (Fig. 9, No. 5). This change consists in the complete union of the basal plates, and may occur in either the five-, four-, or three-basal forms. The formula for complete anchylosis is *abcde*.

2. THEORIES FOR THE EVOLUTION OF THE BASE IN HEXAGONAL CAMERATA

a) *Enlargement of the posterior basal.*—Having in mind the time and place of development of the anal plate, let us examine the

changes its introduction between the posterior radials would probably cause in the posterior basal in the cup of the primitive embryo. Since the zone of potential weakness caused by the enlarging hindgut is evidently in the right-posterior radius of the calyx, there can be but three possibilities for the enlargement of the posterior basal, which are: (i) normal symmetrical enlargement; (ii) enlargement through the anchylosis of a sixth basal factor appearing between the posterior and right-posterior basals; and (iii) enlargement through acceleration of growth in the right- or left-posterior sides.

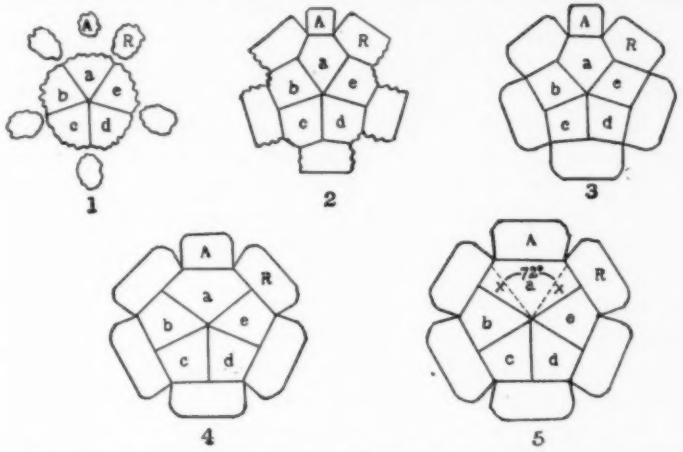

FIG. 10.—Diagrams illustrating modifications in shape and position of the basals and radials by the introduction of the anal plate; wavy lines indicate plate margins not in contact, smooth lines indicate plate margins in contact: 1–4, stages based upon the development of *Antedon;* 5, *Tanaocrinus* stage.

i. When the anal plate came into contact with the posterior basal (Fig. 10, No. 2), mutual trunkation of their apposed margins would take place, perhaps to a slight degree by absorption, but mainly from atrophy and broadening by lateral growth. As the radials and anal came into contact (Fig. 10, No. 3), growth pressure would cause a gradual spreading of the radial cycle at the posterior side, the lateral radials swinging outward and slightly forward (Fig. 10, No. 4), with a hinging motion along the lateral suture margins, until the anal plate reached its full proportionate

size in development (Fig. 10, No. 5). The lateral basals, with their distal angles still in continuous growth-contact with the proximal ends of the radials, would separate slightly and gradually at their bases, as their longitudinal axes swung with the movement of the radials. The posterior basal would also move outward from the axial canal. These movements, however, are not migrational, but are of approximately the same type found in normal growth (see p. 502); for continuous growth along the plate margins, more rapid in the expanding areas than elsewhere, would keep the plate margins in continuous contact as in normal growth.

Since expansion by proximo-lateral growth is obviously not as rapid as by disto-lateral growth, the proximal ends of the basals would probably not be carried out from the center of the cup by growth pressure proportionately as far to the distal ends as they are in normal growth. Thus the proximal ends would apparently be lowered toward the horizontal plane of projection, and the projected angles of the proximal ends, which were 72° in the pentagonal base, would approach 60° in the hexagonal base. With greater expansion in the sarcode and greater plate growth taking place in the posterior region, the proximal angle of the enlarging posterior basal would increase, while those of the lateral basals would decrease through lengthening of their proximo-lateral margins by growth as well as by change in the angle of projection and shifting of their longitudinal axes. This method of basal change is symmetrical, normal, and apparently in keeping with the development in *Antedon* and the early monocyclic and dicyclic Camerata as we now know them.

The first expression of the pent-up energy in the developing intestine seems then to have been used up in a normal expansion of the posterior interray, which in this group proved to be a plane of weakness in the cup. Later, however, when the tendency for spreading was established, this energy was expressed in another direction, and in some of the modern crinoids (*Pentometrocrinus*, etc.) results in an almost complete flattening of the dorsal cup.

ii. The theory of the interpolation of a sixth basal factor to the right of the posterior basal is based upon the appearance of the radianal in that position in *Sagenocrinus*. It requires, first, the

duplication of the posterior basal; secondly, the locking in of the sixth basal in the basal cycle; and, thirdly, closure of the posteriorly directed basal suture by anchylosis. On the ground of possibilities there can be no objection to this hypothesis, for we know that this certainly occurred in *Sagenocrinus*, nor can there be serious objection to the locking in of this plate in the basal cycle, for the radianal of *Pisocrinus* is locked in in the radial cycle. The most serious objection to this theory is that in the series of sutural reappearances in species with a hexagonal base a normal right-posterior basal suture has not been found, although the writer has made careful search for such examples.

iii. The theory of asymmetrical enlargement requires either enlargement of the left side of the posterior basal, or of the right side, which is Wachsmuth and Springer's theory for enlargement. In favor of the first development is the fact that in the Flexibilia Springer has found a general enlargement of the left side of the posterior basal.[1] In favor of the second part of this theory is the development to the right of the radianal in *Pisocrinus*, apparently in the face of the influence of the growing intestine which in the Flexibilia tends to carry this plate to the left of the right-posterior radial. The abundance of evidence Springer has brought in his work on Flexibilia far outweighs the slight evidence shown in *Pisocrinus* and inclines one to believe that factor x might have been added to left of basal *a;* but when we consider the evidence of increasing potency for distortion on the part of the intestine, there is a strong possibility that the intestine may have shoved the posterior basal to the left, as Wachsmuth and Springer believe, and may have at the same time inhibited the tendency of expansion on the part of the right-posterior basal, permitting the posterior basal to enlarge on the right side. We are here involved in a question of directive controls which cannot be readily answered, and, since the posterior basal in *Tanaocrinus* is symmetrically trunkated and developed, the writer is forced to the conclusion that asymmetrical development had not at that time appeared in the posterior basal.

The formula for a base developed upon the first theory is $\overline{x\bar{a}x}$—*b*—*c*—*d*—*e*—, or in shortened form $\bar{a}$—*b*—*c*—*d*—*e*— (Fig. 9,

[1] Ref. 31, p. 496.

No. 6); that of the second theory is *xa—b—c—d—e—*, while those of the third theory are $\overline{ax}$*—b—c—d—e—* for lateral enlargement of the left side, and *xa—b—c—d—e—*for lateral enlargement of the right side.

b) Development of the quadripartite base.—In the evolution of the four-basal, hexagonal base there can be no disagreement, as but one pair of basals, the anterior pair, is anchylosed. Anchylosis in this type of base is generally accompanied by symmetrical reduction of the compound plate and an asymmetrical and compensating enlargement of the apposed basals. The formula for the four-basal type, based upon the theory of symmetrical enlargement of the posterior basal, is $\bar{a}$*—b—cd—e—* (Fig. 9, No. 7); that of Wachsmuth and Springer, *xa—b—cd—e—* (Fig. 1, No. 7).

c) Development of the tripartite base.—In the discussion of the evolution of the tripartite base three theories will be considered: (i) the tortional theory of Wachsmuth and Springer; (ii) the bisection theory; and (iii) theory of atrophy and compensating hypertrophy.

i. Tortion theory: Wachsmuth and Springer's theory may be stated as follows: The equally tripartite base of the hexagonal Camerata originated from an unequally tripartite base of the *Platycrinus* type by the addition of an anal plate, which caused (1) a spreading of the posterior interradius; (2) a tortion of the base which brought the right-posterior and anterior basal sutures respectively into contact with the anal plate and the right-anterior radial; and (3) the addition of a lateral-growth factor (*x*), to the right of the left-anterior basal. The evolution of the base upon this theory may be expressed in formula as follows: *ab—c—de—* to *ab—cx—de—* (Fig. 1, Nos. 3, 9, 10).

Since this theory was thought to have been confirmed by an abnormal example of *Teleiocrinus umbrosus* in which the anal plate is missing and the base, supposedly, reduced to the *Platycrinus* type (*ab—c—de—*), it assumes (1) that the subequally tripartite base did not originate from the hexagonal five- or four-basal forms, but from another line, or (2) that it did originate from them and that an intermediate form existed in which the anal plate was temporarily lost and the base was like that of *Platycrinus*. This

latter assumption demands the loss of factor *x* and anchylosis of two pairs of plates in the five-basal form, as in changing *xa—b—c—d—e—* to *ab—c—de—*, or the factor *x*, the anchylosis of two pairs of plates, and the reappearance of the anterior suture in the four-basal form, as in changing *xa—b—cd—e—* to *ab—c—de—*. Bather in accepting[1] this theory apparently assumes an intermediate step, for in the generic discussion of *Abacocrinus*[2] he says: "From the imagined intermediate step [not from *Abacocrinus* itself], *Periechocrinus* may have been derived by fusion of 2 BB [*two basals*]."

In the review of the evolutional characteristics in the Batocrinidae and Actinocrinidae, we have seen that the anal plate first appeared in the five-basal form of the *ā—b—c—d—e—* type, and that it was probably introduced without other distortional changes than those assumed in the hypothesis here offered (see p. 667). In the four-basal form anchylosis of one pair of basals, the anterior pair, resulted. So far there have been no relative distortional shiftings of the basals or radials except in the posterior region.

Furthermore, there is not throughout the succession of Batocrinoidea and Actinocrinoidea a single species with the *ab—c—de—* type of base. Only in two similarly abnormal specimens, one of *Teleiocrinus umbrosus*, in the Springer collection, the other of *Steganocrinus pentagonus*, in the Walker Museum collection, is the unequally tripartite base belonging to the *ab—c—de—* group found. It does not seem possible, then, that in a succession so clearly outlined the anal plate should temporarily disappear in the imagined[3] intermediate form between *Abacocrinus* and *Periechocrinus*. The reversion and replacement herein implied are entirely out of harmony with the processes of evolution in crinoid development. Can it then be possible that the anterior suture reappeared in the intermediate form, so that shifting of the basals could take place, as believed by Wachsmuth and Springer? We know of no positive instances of the reversion of a phylogenetic trend by the appearance of such an atavistic feature as a new generic or specific character (see p. 544). Since there is apparently no hope along this line of development, let us start with the original *ā—b—c—d—e—* type of

[1] Ref. 3, p. 427, third notice.

[2] Ref. 6, p. 166.

[3] Ref. 6, p. 166.

base, close the left-posterior and right-posterior sutures, and shift the plates in accordance with Wachsmuth and Springer's theory. We are here confronted at once with the fact that neither in *Antedon*, in the five-basal hexagonal forms of monocyclic or dicyclic Crinoidea, nor in the four-basal hexagonal Camerata, has any such shifting taken place. Since the stimulus for widening the posterior interradius has already accomplished its purpose, there is apparently no stimulating cause to accomplish such a shifting, and if there is no such stimulus, there is but one other alternative: the phylogenetic succession as emended by Bather[1] and accepted by Springer[2] is artificial.

Grant for the moment that the succession as outlined is artificial, and starting with the ancestral form as proposed by Wachsmuth and Springer, develop the hexagonal, equally tripartite base from the pentagonal, unequally tripartite base. The anal plate being inserted as proposed, let us follow closely the steps required in the shifting of the basals. The posterior and left-posterior, the right-posterior and right-anterior basals have already anchylosed in pairs, which demands, as we have shown before, closed plate cycles. In order that the right-anterior compound basal *de* may assume a right-posterior position, as Wachsmuth and Springer have affirmed, sufficient expansion must take place between the radials and the basals to permit such shifting, or there must be absorption of the distal angle of this basal, the proximal angles of the radials, or of both coupled with inhibition of plate growth in order to permit their passing. At the same time that widening in the anal area is taking place there must be a compensating widening between the two anterior basals. This change demands a movement of the sarcode on the right side away from the anal plate in the radial cycle and toward it in the basal cycle, which is surely too remarkable a tortion to be deemed possible, especially in forms having the bilaterally symmetrical development shown in the camerate Crinoidea. Furthermore, this theory does not take into consideration the fact that it is the stimulus arising from the push of the rapidly developing intestine against the posterior interradius that has caused the introduction of the anal plate.

[1] Ref. 6, pp. 159–70.

[2] Ref. 25, pp. 193–98.

Let us now turn to a study of the specimen of *Teleiocrinus umbrosus* (Pl. I, Nos. 1, 2, 4, 6) by which Wachsmuth and Springer thought their theory to have been confirmed. Upon careful examination of this specimen grave doubts have arisen in the writer's mind concerning the validity of its assigned orientation. *Teleiocrinus umbrosus* has a central anal tube; therefore use of this as a reference point for orientation is denied. If, however, we consider that the interray in which the abnormality (loss of the anal plate) occurred should perhaps show some variation from the supposedly normal interrays, a different answer to the problem is obtained. Four of the interrays in this specimen show the normal *Teleiocrinus umbrosus* type of development: 1, 2, 2, 2. The fifth interray shows the following arrangement: 1, 3, 4, 2, which varies from the normal posterior interray (*A*, 2, 3, 4, 2) or (*A*, 2, 4, 3, 2) by the loss of but two important plates—the anal plate and one plate of the superimposed pair. There is here too close a parallel to be considered entirely accidental, and it does not seem unreasonable that if some plates are missing from an interray, that interray should show signs of abnormality. If, then, it be assumed that the abnormal interray in this specimen of *Teleiocrinus umbrosus* is the true posterior interray, the basal formula is not *ab—c—de—*, as in *Platycrinus*, but *ab—cd—e—*, for the simple basal is bisected by the plane of the right-posterior interray.

Let us, before going farther, examine the specimen of *Steganocrinus pentagonus* (Pl. II, No. 15; Pl. III, Nos. 1, 2) which, like the specimen just described, has lost its anal plate. *Steganocrinus pentagonus*, unlike *Teleiocrinus umbrosus*, has a slightly eccentric anal tube; the vertical convexity of the posterior interray is much flatter than in the other interrays, and the interbrachial plates are ornamented at a lower level by low sharp nodes. If, then, this specimen be oriented according to the position of the anal tube, convexity of interrays, and ornamentation, the basal formula is found to be, not *ab—c—de—*, as in *Platycrinus*, but *b—cd—ea—*, for the simple basal is bisected by the plane of the left-posterior interray. In *Teleiocrinus umbrosus* the posterior basal has anchylosed with the left-posterior basal; in *Steganocrinus pentagonus* it is anchylosed with the right-posterior basal. The reversion herein

implied is very close to being a solution for the problem of the appearance of the posteriorly directed basal suture, and we need no longer confuse the issue with origin from *Platycrinus* or other three-basal forms of the *ab—c—de—* type.

It seems then that Wachsmuth and Springer's theory for the development of the hexagonal, tripartite base does not meet the requirements of present needs, and we may turn to a discussion of the remaining theories.

ii. Bisection theory: Briefly stated, the bisection theory assumes that the posteriorly directed basal suture resulted from the bisection of the posterior basal in a quadripartite base, and anchylosis of the portions of the posterior basal to the adjacent basals. This development may be expressed in formula as follows: $\bar{a}$*—b—cd—e—* through *a—b—cd—e—a—* to *ab—c—d—ea—*. The first objection to this theory is that there are no known instances of the bisection of a growing plate in modern Echinodermata. The second objection is that in the examples of recurrence of sutures by delayed anchylosis there are no instances of the reappearance of a normal right-posterior basal suture when the posterior suture is present (see Pls. II, III), although the writer has, as previously stated, made careful search for such examples. This theory and any theory based upon the assumption of plate splitting as a phylogenetic characteristic may apparently be abandoned as a factor in the development of Crinoidea.

iii. Theory of atrophy and compensating hypertrophy: The theory of atrophy and compensating hypertrophy is that the posteriorly directed basal suture and the subequally tripartite base of the hexagonal, monocyclic typical Camerata arose from the atrophy of the right half of the enlarged posterior basal, a compensating enlargement of the right-posterior basal, and the anchylosis of the posterior and left-posterior basals.

This theory is based upon (1) the general presence of atrophy in the right side of the posterior basal in Flexibilia; (2) the non-appearance of the right-posterior basal suture in the specimens showing reappearance of lost sutures through delayed anchylosis, and (3) evidence showing the derivation of *Dichocrinus* from *Platycrinus* stock.

In speaking of the base in the Flexibilia, Springer says:

> The posterior basal upon which it [the anal series] rests is excavated into a sort of shallow socket, like the articulating face of a radial, on the right shoulder of the plate, so that we will usually see a small tongue or angle of that plate rising up to the left of the base of the anal plate higher than to the right; or, if the socket-like excavation is not so plain as this, the upper edge of the basal is distinctly sloped to the right.[1]

Furthermore, in *Abacocrinus* the writer has found a marked reduction of the right side of the posterior basal and a compensating enlargement of the right-posterior basal (Pl. II, No. 7). There is here shown a marked tendency for the stimulus arising from the developing intestine to inhibit the growth of the posterior basal upon the right side and to permit the growth of the adjacent right-posterior basal.

Upon two of the accompanying plates (Pls. I, II) are illustrated the specimens upon which the evidence for sutural reappearance through failure of anchylosis is based. These illustrations show clearly the appearance of the anterior suture in *Melocrinus*, *Actinocrinus*, *Steganocrinus*, and *Hexacrinus*, and this suture is so often represented that it cannot be ascribed to any other cause. The appearance of this suture could only be accounted for upon Wachsmuth and Springer's theory by plate splitting, a supposition which is absolutely without foundation. It will furthermore be noticed that in no instance do the posterior and right-posterior sutures appear in the same specimen. Both sutures are sometimes absent, but in general the posterior suture is present and the right-posterior absent. The reappearance of the anterior suture and the failure of the right-posterior suture to reappear in any specimen in which the posteriorly directed suture is present, and in which other combinations of lost and normal sutures do appear, is the evidence upon which the theory of atrophy and compensating hypertrophy is based, and is here submitted as evidence that plate shifting such as Wachsmuth and Springer assumed probably did not take place, but that the right-posterior basal suture assumed a posterior position upon partial atrophy of the posterior basal and compensating hypertrophy of the left side

[1] Ref. 31, p. 496.

of the right-posterior basal. The formula of the tripartite, hexagonal base, upon the theory of atrophy and compensating hypertrophy, is *ab—cd—ex—*.

The explanation of the reversion implied in the abnormal specimens of *Teleiocrinus umbrosus* and *Steganocrinus pentagonus* may upon this theory be readily explained. Upon loss of the anal plate, stimulus for shifting the posterior basal suture was also lost, but the tendency for anchylosis of the anterior basals established in the early Batocrinoidea was not changed. Anchylosis then took place in as nearly normal a manner as possible, one of the postero-lateral sutures only in each specimen failing to close.

It will be noted that in the preceding discussion no mention has been made of the proportionate amount of growth in the radials, the anal, and the enlarged basals. This is because some misconception has arisen concerning their development, owing to the assumption that the basal outline is a regular hexagon. From careful measurements of the proximal diameter of the radials and anal in over five hundred specimens of Batocrinidae and Actinocrinidae it was found that in general the largest plates in the radial cycle are the antero-lateral radials, while the postero-laterals or the anal are the smallest in the radial cycle. Since the posterior radials are reduced by the interpolation of the anal plate (see p. 549) and the margins of the posterior basal do not extend beyond the center of these radials, it is evident that the posterior basal did not enlarge to a width equal to that of two of the other basals, as Wachsmuth and Springer have assumed, nor is the base a regular hexagon. The reduction of the posterior basal and the compensating enlargement of the right-posterior basal do not then require a formidable amount of plate readjustment, especially when we remember what readjustments have taken place in *Pisocrinus* (see p. 535).

3. EVOLUTION OF THE BASE IN THE HEXACRINIDAE

The evolution of the base in the Hexacrinidae is not as simple a problem as the evolution of the base in the Batocrinidae, for the phylogenetic succession is not as clearly defined. The general affinities of the Hexacrinidae are with the Platycrinidae, but the paths of evolution resulting in the subequally tripartite and bipar-

tite bases are obviously so different that it is better to consider their basal developments separately.

a) Evolution of the tripartite base.—As the evolution of the tripartite base in the Hexacrinidae has resulted in essentially the same type of base as in the Batocrinidae, the same theories of descent will be considered; these are Wachsmuth and Springer's theory of torsion, and the theory of atrophy and compensating hypertrophy.

i. Torsion theory: Wachsmuth and Springer's theory for the evolution of the tripartite, hexagonal base of the Hexacrinidae is: Upon interpolation of the anal plate in some form having the *Platycrinus* type of base (*ab—c—de—*), spreading of the radial cycle at the posterior side was accompanied by a spreading of the basal cycle at the anterior side, thus causing the compound, dextrolateral basal to shift so that the right-posterior suture came into contact with the anal plate, and the anterior suture into contact with the right-anterior radial, while at the same time compensating growth of the left-anterior basal filled the vacant space. This metamorphosis may be shown diagrammatically by changing formula *ab—c—de—* to *ab—cx—de—* (Fig. 1, Nos. 3, 9, 10). The method of development is the same as was postulated by Wachsmuth and Springer for the development of the base in the Batocrinidae and the same objections are in force, but as the relationship of the three-basal Hexacrinidae is apparently with the Platycrinidae, these objections will be reconsidered.

The strongest objection to the torsion theory is that the stimulus for widening the posterior interradius is due directly to the oblique pressure of the growing hind-gut upon the right-posterior radius and posterior interradius, and cannot therefore produce a spreading between the anterior basals. The second objection is that in the two cases of sutural reappearance, by delayed anchylosis, in *Hexacrinus* (Pl. III, Nos. 5, 6) the right-posterior suture does not appear, although in the specimen (Pl. III, No. 5), showing the reappearance of the left-posterior sutures it would naturally be expected. Wachsmuth and Springer's theory does not then seem entirely adequate in explaining the formation of this base, and we may consider the second theory.

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i. Torsion theory: Wachsmuth and Springer's theory for the evolution of the tripartite, hexagonal base of the Hexacrinidae is: Upon interpolation of the anal plate in some form having the *Platycrinus* type of base (*ab—c—de—*), spreading of the radial cycle at the posterior side was accompanied by a spreading of the basal cycle at the anterior side, thus causing the compound, dextrolateral basal to shift so that the right-posterior suture came into contact with the anal plate, and the anterior suture into contact with the right-anterior radial, while at the same time compensating growth of the left-anterior basal filled the vacant space. This metamorphosis may be shown diagrammatically by changing formula *ab—c—de—* to *ab—cx—de—* (Fig. 1, Nos. 3, 9, 10). The method of development is the same as was postulated by Wachsmuth and Springer for the development of the base in the Batocrinidae and the same objections are in force, but as the relationship of the three-basal Hexacrinidae is apparently with the Platycrinidae, these objections will be reconsidered.

The strongest objection to the torsion theory is that the stimulus for widening the posterior interradius is due directly to the oblique pressure of the growing hind-gut upon the right-posterior radius and posterior interradius, and cannot therefore produce a spreading between the anterior basals. The second objection is that in the two cases of sutural reappearance, by delayed anchylosis, in *Hexacrinus* (Pl. III, Nos. 5, 6) the right-posterior suture does not appear, although in the specimen (Pl. III, No. 5), showing the reappearance of the left-posterior sutures it would naturally be expected. Wachsmuth and Springer's theory does not then seem entirely adequate in explaining the formation of this base, and we may consider the second theory.

ii. Theory of atrophy and compensating hypertrophy: This theory has been fully considered in the preceding discussion of the formation of the tripartite base in the Batocrinidae and need not be restated. It requires the interpolation of an anal plate in the radial cycle, partial atrophy of the right half of the posterior basal, a compensating enlargement of the right-posterior basal to bring the right-posterior basal suture into contact with the anal plate, and perhaps the closure of one or more of the primary sutures. However, when this theory is applied to the supposed phylogenetic succession resulting in the Hexacrinidae, a peculiar difficulty is encountered. The *Platycrinus* type of base (*ab—c—de—*) in changing to the subequally tripartite base (*ab—cx—de*) demands upon this theory the reappearance of the right-anterior basal suture. Sutural reappearance as a phylogenetic character is, however, not considered a probability, and the second theory also seems inadequate to meet the demands of this problem. There is, however, another phase of the problem which must not be overlooked, and that is the possibility that *Hexacrinus* and *Arthrocantha* did not originate from one of the Platycrinidae with an *ab—c—de—* type of base. This suggestion is not to be considered as a means of confusing the issue and saving the writer's hypothesis; it is inserted to call attention to the fact that there is practically nothing known about the ancestors of the Platycrinidae nor the predecessors of the Silurian genera belonging to that family. The evidence derived from sutural reappearance by delayed anchylosis in the Batocrinidae and Hexacrinidae is such that there seems to be but one possible conclusion to be drawn, which is that *Hexacrinus* and *Arthrocantha* probably originated, not from a three-basal form of the *ab—c—de—* type, but from a simple five-basal type. The changes required in the suggested line of descent consist of: interpolation of the anal plate by portional migration; closure of the anterior and left-posterior basal sutures; partial atrophy of the posterior basal; and compensating hypertrophy of the right-posterior basal to shift the right-posterior suture to a posterior position (Fig. 9, Nos. 1, 7*a*, *b*).

b) *Evolution of the bipartite base.*—Wachsmuth and Springer's theory[1] for the origin of the bipartite, hexagonal base is stated as

[1] Ref. 39, p. 56.

follows: "The bipartite base is probably derived from the tripartite, which preceded it in time, and *x*, which in the latter constituted a part of *c*, is united with *de*, and *ab* with *c* [Fig. 1, Nos. 11, 12]." Thus upon the shifting of plate *de* the tendency for the enlargement of plate *c* was inhibited, and a compensating growth of plate *de* filled the space formerly filled by the enlargement of plate *c*. This metamorphosis is shown by changing formula *ab—cx—de—* to *abc—xde—*.

To this theory, however, there are the same objections that were encountered in that of the formation of the tripartite base in both the Batocrinidae and the Hexacrinidae. Torsion such as is assumed for the shifting of the compound plate *de* is apparently impossible, as the stimulus for enlarging the posterior interradius is due to the pressure from the growing hind-gut and cannot affect the anterior basal sutures. Furthermore, the examples of suture reappearance in the bipartite base show the potential presence and position of all but the right-posterior suture (Pl. III, Nos. 8, 9, 10). Wachsmuth and Springer's theory again does not seem adequate to explain the changes which have taken place and we may consider the theory of atrophy and compensating hypertrophy.

When the theory of atrophy and compensating hypertrophy, which has been thoroughly discussed, is applied to the phylogenetic succession as formulated by Wachsmuth and Springer, it also meets with the same trouble that was encountered in considering the evolution of the tripartite base. In this case the anterior basal suture must reappear as a phylogenetic character. Phylogenetic reappearance of a suture lost through anchylosis is, however, considered impossible, and the phylogenetic succession as postulated by Wachsmuth and Springer must be examined.

There are, it is true, many similar characteristics in the Hexacrinidae having tripartite and bipartite bases, but when the tegminal structures of the *Hexacrinus* and *Dichocrinus* are compared there is a marked difference. *Hexacrinus* has a ridged tegmen composed of medium-sized plates, and the ambulacrals are usually partially incorporated. *Dichocrinus*, however, has in its earliest expression in the Kinderhook a flexible tegmen composed of minute interambulacrals and unincorporated ambulacrals. *Dichocrinus* therefore apparently could not have originated from the

Devonian expression of *Hexacrinus*, as the reversion from a camerate type of tegmen to the flexible type, and a redevelopment of the camerate type as shown in later forms of *Dichocrinus* and more strongly in its descendants, *Talarocrinus*, etc., are scarcely probable. When, however, *Dichocrinus* (Pl. III, Nos. 12, 15) is compared with a Kinderhook species of *Platycrinus*, namely *P. symmetricus*, (Pl. III, Nos. 13, 14), such a remarkably close parallel in calyx structure is noted that with the insertion of an anal plate and proper modification of the base *P. symmetricus* could scarcely be distinguished in calyx structure from *Dichocrinus inornatus*. However, some species of *Dichocrinus* have uniserial arms, and all have a circular stem. *Dichocrinus* could not then have originated from the immediate ancestor of *P. symmetricus*, but from a somewhat earlier stage where the stem was circular, the arms uniserial, and the base of the *ab—c—de—* type. Hence a new theory for the origin of the bipartite, hexagonal base is suggested:

Dichocrinus and its descendants probably originated from some genus of the Platycrinidae which had a circular stem, flexible tegmen, branching uniserial pinnulate arms, and a base of the *ab—c—de—* type. The hexagonal, tripartite base originated by interpolation of the anal plate in the radial cycle by portional migration, closure of the left-anterior suture, partial atrophy of the right side of the posterior basal, and a compensatory hypertrophy of the left side of the right-posterior basal which shifted the right-posterior basal suture to a posterior position. This metamorphosis is expressed in changing formula *ab—c—de—* to *abc—dex—* (Fig. 9, Nos. 4, 4*a*, *b*).

4. THE SUCCESSION OF BASAL CHANGES IN THE PLATYCRINIDAE AND THE HEXACRINIDAE

The succession of basal changes in the Platycrinidae and the Hexacrinidae seems, from the evidence herein offered, to have followed a different line from that postulated by Wachsmuth and Springer, and the following succession is suggested.

The earliest Platycrinidae, as shown by the ontogenetic development of *Platycrinus*, had a simple pentagonal base of the *a—b—c—d—e—* type and a circular stem. Before the Niagaran (Silurian) this genus gave rise to the *Platycrinus* type of base (*ab—c—de—*)

in *Coccocrinus*, etc., and to the *Stephanocrinus* type of base (*ea—bc—d—*) in *Hapalocrinus*. Anchylosis of the basals in these forms was accompanied by reduction of the compound plate either by superficial or by deep-seated atrophy, and compensating hypertrophy of the simple basal. From *Coccocrinus* two lines of descent seem to have originated: the one culminating in *Platycrinus*, etc., with the *ab—c—de—* (Fig. 9, No. 4) type of base and an elliptical stem; the other culminating in *Dichocrinus* with its hexagonal, bipartite base (*abc—dex—*) (Fig. 9, No. 4*b*) and a circular stem. Interpolation of the anal plate in Dichocrinus is marked by reduction of the posterior radials, and the base is not a regular hexagon. The origin of the hexagonal genera with the tripartite base *ab—cd—ex—* (Fig. 9, No. 7*b*) is doubtful, but they were probably derived from an early branch of the primitive Platycrinidae, in which the base was a simple pentagon of the *a—b—c—d—e—* type and the stem circular.

SUMMARY OF CONCLUSIONS

In the preceding discussion the writer has attempted to portray the various stages of development through which the basal plates of the monocyclic Camerata have passed, and to explain the processes by which these results were obtained. Many of the theories herein set forth will undoubtedly be modified by the discovery of new evidence, and this study is offered merely as a working hypothesis upon which, perhaps, a stronger classification of the Crinoidea may be erected. As a result of this study the following conclusions have been reached:

1. The ancestor of the monocyclic Camerata was a simple, generalized crinoid with pentamerous symmetry.

2. The base of the pentagonal Camerata is not the result of reversion from an intermediate hexagonal stage, but is in a primitive condition as far as influence of the anal plate is concerned.

3. The anal plate is of secondary origin, and originated by primary interpolation between the latero-distal margins of the posterior radials.

4. The hexagonal base of the monocyclic Camerata resulted from the separation of the posterior radials and trunkation of the

posterior basal by the anal plate, the anal plate having been interpolated by portional migration in the space created by the demand of the hind-gut for enlargement.

5. The widening of the posterior basal upon interpolation of the anal plate was bilaterally symmetrical.

6. The quadripartite, hexagonal base resulted from the anchylosis of the anterior pair of basals in a hexagonal genus with a pentapartite base.

7. The posteriorly directed basal suture in the subequally, tripartite and bipartite, hexagonal bases is the homologue of the right-posterior basal suture in the pentapartite and quadripartite bases, which has shifted its position through atrophy of the right half of the posterior basal and a compensating hypertrophy of the left side of the right-posterior basal.

8. The basal sutures lost through anchylosis are potentially present in the basal cup, and liable to reappear in individual cases of delayed anchylosis, but not as a phylogenetic character.

9. The tripartite, hexagonal base in the Batocrinidae resulted from the appearance of the posteriorly directed basal suture (see 7) in a quadripartite base, accompanied by closure of the anterior and left-posterior basal sutures.

10. The hexagonal, tripartite base of the Hexacrinidae resulted from the interpolation of an anal plate by portional migration, through shifting of the right-posterior basal suture to a posterior position, and closure of the anterior and left-posterior basal sutures, in a simple platycrinid with a pentapartite base.

11. The bipartite, hexagonal base in the Hexacrinidae resulted from interpolation of the anal plate by portional migration, shifting of the right-posterior basal suture to a posterior position, and closure of the right-anterior basal suture, in a platycrinid with a pentagonal, unequally tripartite base.

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DISCOVERY OF THE GREAT LAKE TROUT, *CRISTIVOMER NAMAYCUSH*, IN THE PLEISTOCENE OF WISCONSIN

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Some fish remains consisting of a portion of a skull and a number of associated elements, from an interglacial clay deposit in Dunn County, Wisconsin, were recently sent to me for identification by Dr. S. Weidman, of the State Geological Survey of Wisconsin. They turned out to be remains of the great lake trout, *Cristivomer namaycush*, a species now living in Wisconsin waters. They are therefore of interest as carrying back the history of this species to Pleistocene times. Through the kindness of Dr. Weidman, I am permitted to present the following notes on the specimens.

The remains consist of a portion of a skull of a fish about two feet in length, with most of the jaw elements belonging to it, and a number of thin and more or less fragmentary bones pertaining to the opercular and hyoid series. Associated with these remains was a toothed fragment of the jaw of another species of fish, as yet undetermined.

The genus *Cristivomer* is distinguished from all other trouts and salmons (family Salmonidæ), by the shape of the vomer. This element, in side view, and held with the oral face up, is boat-shaped, with a raised crest armed with strong teeth, extending in the median line of the oral face, from the head of the bone backward (Fig. 1*b*). By this element alone the remains are identifiable as belonging to genus *Cristivomer;* and all doubt whatsoever is removed on comparing the other bones with a disarticulated skull of the living lake trout. The correspondence bone for bone is very close, extending to details, so that the fossil form cannot be separated even as a variety from the existing one.

No detailed discussion of the several elements seems necessary; reference may be made to Fig. 1, in which the better preserved

FIG. 1.—*Cristivomer namaycush*. Jaw elements belonging to a single fish, ×⅓. Pleistocene; Menomonie, Dunn County, Wisconsin.

a, right maxilla; *b*, vomer, in oral view; *c*, left premaxilla; *d*, teeth from mandible and vomer; *e*, left mandible, outer view; *f*, right mandible, inner view.

of the elements are shown. The parasphenoid is also preserved. It is seen on the under side of the posterior portion of the skull roof, which is the only part of the upper skull surface preserved. This element also agrees closely with that of the existing species.

The discovery of fossil remains of *Cristivomer* is interesting but not unexpected; for the existing species has a wide range in the colder waters of north temperate America, extending into the sub-arctic region. Jordan gives the distribution as follows: "All the larger lakes from New England and New York to Wisconsin, Montana, the Mackenzie River, and in all the lakes tributary to the Yukon in Alaska."[1]

From the extent of this range one would have inferred that the species must have had a long time in which to "spread out" over such an area, and hence that it dated back to at least Pleistocene times. The finding of this specimen proves that this was the case. It shows, moreover, that the genus existed during glacial times in the same region as today, so that its antecedent history—whether it arose in the same region, or wandered into it from somewhere else—dates back to an even earlier time.

The specimen is preserved in the collection of the Wisconsin Geological Survey. The following measurements may be of use for future reference:

VOMER	
Length	44 mm.
Width at neck	12
PREMAXILLA (Left)	
Length, measured along toothed edge	33
Height, at posterior end	27
MAXILLA (Right)	
Total length	105
Length exclusive of anterior process (measured along toothed margin)	95
MANDIBLE	
Both are defective posteriorly; the left as far as preserved measures	95

[1] Jordan, *Guide to the Study of Fishes*, II, 115.

The specimen was collected from a clay bed at Menomonie, Dunn County, Wisconsin. At this locality these beds are from twenty to forty feet in thickness. The following notes regarding them were kindly supplied by Dr. S. Weidman to whom I am also indebted for the geological section here reproduced (Fig. 2).

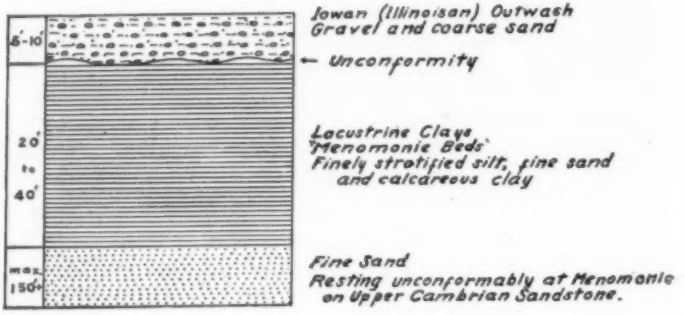

FIG. 2.—Section at Menomonie, showing relations of Pleistocene lacustrine clay beds.

The clay beds are located in the valley of Red Cedar River and have been utilized extensively for many years for the manufacture of brick. The formation consists of finely stratified sand, silt, and clay, usually containing from 5 to 10 per cent of calcium and magnesium carbonate. In other localities the calcareous content is much higher and reaches 20 to 30 per cent. The physical and chemical character of the deposit, as well as the occurrence of the fish remains, indicate the lacustrine origin of the formation. Similar deposits are widespread in Wisconsin and the adjoining states, and have very generally been classed as lacustrine or estuarine. . . . .

The relations of the lacustrine clay ("Menomonie beds") to the overlying Iowan (Illinoisan) glacial gravels indicate that the probable age of the clay is the Interglacial stage between the Kansan and the Iowan (Illinoisan), that is, between the second and third glacial stages of the Pleistocene. No definite relations of the clay beds at Menomonie to the Kansan is exhibited, the border of the Kansan being located 10 or 12 miles to the west, but, based in part on other geologic data, the above inference as to the age seems warranted. The stratigraphic position of the clay beds, in which the species of fish, *Cristivomer namaycush*, is found is therefore near the middle of the Pleistocene series, and as variously estimated in years this particular deposit is probably between 250,000 and 500,000 years old.

Besides the remains of fish, there have been found in the Menomonie clay beds the remains of various mammals such as the elephant, mastodon, reindeer, caribou;[1] the bones of other mammals, the leg bone of a bird, and also fragments of wood identified as spruce.

The fossil remains of the land mammals and of forest trees found in the clays are only in fragmentary pieces, indicating the fact that these were carried some distance by streams, or currents along the lake shore, and dropped into the bed of the old lake.

The remains of the fish, on the other hand, are fairly complete specimens, and seem clearly to indicate that these fish lived in the lake in which the clays were deposited.

[1] *Rangifer*, probably an extinct species, is represented by both male and female antlers, the latter identified by Dr. O. P. Hay.

ASSUMPTIONS INVOLVED IN THE DOCTRINE OF ISOSTATIC COMPENSATION, WITH A NOTE ON HECKER'S DETERMINATION OF GRAVITY AT SEA[1]

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[1] Criticisms of the conception of isostatic compensation from other viewpoints than those here presented are those of Professor T. C. Chamberlin ("Diastrophism and the Formative Processes," *Jour. Geol.*, XXI [October–November, 1913], 577–87; November–December, 1913, pp. 673–82, and succeeding numbers); and those of Professor Joseph Barrell ("The Strength of the Earth's Crust; Part I," *ibid.*, XXII [January–February, 1914], 28–48, and succeeding numbers), which appeared after its formulation. A sharply critical mathematical discussion of Hayford's trial hypothesis, used in fixing the depth of complete compensation, had already been published (Harmon Lewis, "The Theory of Isostacy," *ibid.*, XIX [1911], 603–26). Hayford's rejoinder appeared in the *Journal of Geology* in 1912 (XX, 562–78).

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INTRODUCTION

A rigid versus a plastic earth shell.—The doctrine of isostasy is an expression of disbelief that the outer shell of the lithosphere is sufficiently strong to support the protuberances upon its surface. An added idea is that, since it is a failing structure, it is sensitive to surface transfers of rock material and responds with a subsidence beneath freshly loaded areas and with corresponding elevation within denuded districts. It should never be forgotten that this theory was conceived at a time when belief in a liquid interior of our planet was general, and that its adjustment to the modern view of a rigid earth is a matter of the last decade only. Probably the fact which more than any other has compelled geologists to consider the question of possible high plasticity within the earth's outer shell is the great thickness of shallow-water deposits that have been laid down in geosynclines. Although to some extent the recent recognition of the large importance of continental deposits within ancient sedimentary formations has required a modification of earlier assumptions, there is still a call for some explanation of the apparent balance which has been maintained between subsidence and the quantity of deposited material within the basins of sedimentation. Obviously two contrasted hypotheses may be offered. Upon the one hand, it may be assumed that the adjustments in

level are the *cause* of the increased denudation and deposition (doctrine of high rigidity); and, upon the other hand, it may be assumed that these changes in level are the *effect* and not the cause (doctrine of high plasticity—isostasy).

While the name isostasy is of American origin[1] and the crystallization of ideas always connected in time with the providing of a pigeonhole for their assembling has been notably strong in this country, the conception itself is much older and has long occupied the attention of geologists in both Europe and America.[2] It appears to have first found full expression a half-century earlier,[3] and it has ever since played an important rôle in the fields of geodesy and geology. From the failure of astronomic and geodetic locations of position accurately to correspond, and from the "anomalies" of pendulum observations—the so-called "anomalies" of deflection of the vertical and of gravity (Δg.)—it has from the beginning drawn most of its support. Woodward, writing in 1889, says: "In general terms we may say that the difficulty in the way of the use of pendulum observations still hinges on the treatment of local anomalies and on the question of reduction to sea-level."[4]

Pratt's hypothesis.—The remarkable anomalies in the deflection of the plumb line which were discovered in Northern India along the base of the Himalayas led Archdeacon Pratt in 1859[5] to the rather astounding assumption that a mass of less density lies beneath this great protuberance upon the lithosphere. Had the venerable archdeacon conceived the earth to be rigid, as is generally held today, it is not very likely that he would have arrived at this

[1] C. E. Dutton, "On Some of the Greater Problems of Physical Geology," *Bull. Phil. Soc. Wash.*, II (1889), 51–64.

[2] For an excellent summary of the evolution of thought along this line, see F. L. Ransome, "The Great Valley of California: A Criticism of the Theory of Isostasy," *Bull. Dept. Geol. Univ. Cal.*, I, No. 14 (1896), 371–428.

[3] Sir John F. W. Herschel, "Letter to C. Lyell, Esq.," *Phil. Mag.*, II (1837), 212–14.

[4] R. S. Woodward, "The Mathematical Theories of the Earth," *Am. Jour. Sci.* (3), XXXVIII (1889), 341.

[5] John Henry Pratt, "On the Deflection of the Plumb-Line in India Caused by the Attraction of the Himalaya Mountains and of the Elevated Regions Beyond: and Its Modification by the Compensating Effect of a Deficiency of Matter Below the Mountain Mass," *Phil. Trans.*, 1859, pp. 745–96.

conclusion. He assumed further that, since the earth's crust is supposed to be in hydrostatic equilibrium, a level surface must be considered as existing somewhere beneath the crust upon which the pressure of the masses lying above is everywhere the same.[1] This convenient idea of compensation of gravity variations in a deficiency of mass beneath the surface in some cases, and an excess in others, has played a large rôle in subsequent geodetic studies and is generally referred to as Pratt's hypothesis.

In America the measurements of gravity made by Putnam along the line of the Transcontinental Survey have been studied with much thoroughness by Gilbert, who has been led to the belief that a considerable measure of compensation exists.[2] He says:

> The measurements of gravity appear far more harmonious when the method of reduction postulates isostasy than when it postulates high rigidity. Nearly all the local peculiarities of gravity admit of simple and rational explanation on the theory that the continent as a whole is approximately isostatic. Most of the deviations from the normal arise from excess of matter and are associated with uplift. . . . . The fact that the six stations from Pike's Peak to Salt Lake City, covering a distance of 375 miles, show an average excess of 1,345 rock feet indicates greater sustaining power than is ordinarily ascribed to the lithosphere by the advocates of isostasy [pp. 73–74].

THE HAYFORD CONCEPTION OF ISOSTATIC COMPENSATION

Scope of Dr. Hayford's investigations.—Attention has been focused anew upon the subject of isostasy by the papers of Dr. John F. Hayford, lately inspector of geodetic work and chief of the Computing Division of the United States Coast and Geodetic Survey, and now dean of the College of Engineering at Northwestern University. His investigations have treated of the figure of the earth and isostasy, and are now deservedly well known on the basis of labors extending over a considerable period of years and published in a series of official monographs and briefer summary articles.[3]

[1] This is essentially Helmert's statement of Pratt's hypothesis (*Sitzungsber. Berliner Akad.*, 1908, p. 1060).

[2] G. K. Gilbert, "Notes on the Gravity Determinations Reported by Mr. G. R. Putnam," *Bull. Phil. Soc. Wash.*, XIII (1895), 61–65.

[3] "The Form of the Geoid as Determined by Measurements in the United States," *Report of the Eighth International Geographic Congress, Washington, 1904* (Government

The writer shares with many others a natural pride in this notable achievement of American research, which has attracted attention by reason both of the large scale of its operations and of its thorough and painstaking execution. With the conclusions concerning the figure of the earth this paper is not especially concerned. It is with reference to Hayford's theoretical deductions within the realm of geophysics and geology upon the basis of Pratt's hypothesis of compensation that the writer would offer suggestions, particularly concerning the fundamental assumptions of which no account is taken in Hayford's papers. In his later article in *Science*—a presidential address—geologists are informed by Dr. Hayford that they have no recourse but to accept his conclusion. We quote:

> Within the past ten years geodetic observations have furnished positive proof that a close approximation to the condition called isostasy exists in the earth and comparatively near the surface [p. 199].
>
> The geodetic observations show that the isostatic compensation under the United States is nearly complete. It is not merely a compensation of the continent as a whole, it is a compensation of the separate, large, topographic features of the continent [p. 200].
>
> The compensation may properly be characterized as departing from completeness only one-tenth on an average [p. 201].

Elsewhere in the article over- or under-compensation is stated not to exceed that of a mass of rock strata 250 feet in thickness, on an average, and that the limiting depth of compensation is 122 km. (76 miles).

Printing Office, 1905), pp. 535–40; "The geodetic Evidence of Isostasy," *Proc. Wash. Acad. Sci.*, VIII (1906), 25–40; "The Earth a Failing Structure," *Bull. Phil. Soc. Wash.*, XV (1907), 57–74; "The Figure of the Earth and Isostasy from Measurements in the United States," *Dept. Com. and Labor, Coast and Geod. Surv.* (Washington, 1909), pp. 1–178, maps; "Supplementary Investigation in 1909 of the Figure of the Earth and Isostasy," *ibid.* (Washington, 1910), pp. 1–80, maps; (with William Bowie) "The Effect of Topography and Isostatic Compensation upon the Intensity of Gravity," *ibid.*, Special Publication No. 10 (1912), pp. 1–132, maps; William Bowie, "Effect of Topography and Isostatic Compensation upon the Intensity of Gravity" (2d paper), *ibid.*, Special Publication No. 12 (1912), pp. 1–28, maps; "The Relations of Isostasy to Geodosy, Geophysics, and Geology," Science, XXXIII (1911), 199–208; "Isostasy, Rejoinder to the Article by Harmon Lewis," *Jour. Geol.*, XX (1912), 562–78. An outline of Hayford's studies from a very sympathetic standpoint is G. K. Gilbert's "Interpretation of Anomalies of Gravity," *Prof. Paper No. 85 C, U.S. Geol. Surv.*, 1913, pp. 29–37, Pl. 4.

Hayford's categorical statements reach their culmination in the following:

> These are the facts, established by abundant geodetic evidence. These facts may not be removed or altered by showing that difficulties are encountered when one attempts to make them fit existing theories, geological or otherwise. The theories must be tested by the facts and modified if necessary [p. 201].

Methods and assumptions within the field of the exact sciences.—Inasmuch as Dr. Hayford's statement last cited raises a question concerning the comparative reliability of the data obtained from geodetic and from geological observations, it may perhaps be pointed out that geologists have before been warned of the fallacy of their conclusions by workers in the field of the so-called exact sciences. Two fairly recent instances will suffice, though it would be easy to cite others.

With a degree of assurance which was perhaps warranted by his pre-eminence in research, the late Lord Kelvin served notice upon geologists that the longest period that could by any possibility be allowed them as representing time since the beginning of life upon the globe was a hundred million years, with a probability that it could not exceed twenty million years;[1] and this figure was soon reduced by Professor Tait to ten million years.[2] With the question of whether this allowance is adequate we are not at the moment concerned, since the developments in the realm of physics have destroyed the value of Kelvin's argument. At the meeting of the British Association held at Winnipeg in 1909, Sir J. J. Thomson, referring in his presidential address before that body to studies of radium by Rutherford and others, showed how Kelvin's argument was based upon incomplete evidence and must now be abandoned in view of the new light which has been shed upon the problem.[3]

It was Helmholtz, another conspicuous champion of the exact sciences, who stated that the atmospheric envelope of the earth could not extend above an altitude of 27 or 28 km., since the temperature gradient required that the absolute zero of temperature

[1] Sir William Thomson, "The Age of the Earth," annual address to Victoria Institute, *Phil. Mag.*, 1899, p. 66; also, *Popular Lectures and Addresses*, II, 64.

[2] *Recent Advances in Physical Science*, p. 174. See rejoinder by A. Geikie, *Landscape in History and other Essays* (1905), pp. 206–8.

[3] *Rept. Brit. Ass'n Adv. Sci., Winnipeg Meeting, 1909* (1910), pp. 27–28.

should be reached at that level.[1] From actual sounding of the atmosphere we now know that the convective zone within which the temperature gradient is essentially adiabatic ends abruptly at an altitude ranging from 9 to 18 km., and that the envelope extends to at least 70 km.,[2] with nearly isothermal conditions above the convective zone.

From these examples and others which might be cited, we should learn that while the methods of "exact science" may not be lacking in precision, the assumptions which enter into the solutions, whether they are used consciously or not, possess the same measure of fallibility as those employed in other fields of science. It is therefore with assumptions unconsciously made by advocates of isostatic compensation that this paper will deal.

Hayford's negative argument for a failing earth, based upon data now shown to be inapplicable.—In his paper entitled "The Earth a Failing Structure," Hayford has shown us how his conclusions and those of the late Sir George Darwin dealing with the same subject are diametrically opposed to each other, for the reason that the basal assumptions differ so widely. In the same paper six negative reasons are given why the earth must be a failing structure; that is, be incapable of supporting its protuberances by virtue of its rigidity. These reasons may be reduced to one and stated in this form: Even if the earth throughout had the strength of granite, it would upon the basis of known tests be incapable of supporting without failure the loads upon it. Since this statement was made, studies by Bridgman[3] and Adams[4] have shown that under hydrostatic conditions of compression such as must be conceived to exist within the earth the crushing strengths of materials are enormously enhanced over those derived from tests in which no lateral constraint is imposed—the data employed by Hayford. The studies

[1] Cf. A. Wegener, *Thermodynamik der Atmosphäre* (1911), pp. 109, 185.

[2] W. S. Bruce, *Polar Exploration* (London, 1911), pp. 210–11.

[3] P. W. Bridgman, "The Collapse of Thick Cylinders under hydrostatic Pressure," *Physical Review*, XXXIV (January, 1912), 1–24.

[4] F. D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (February–March, 1912), 97–118. See also L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior, *ibid.*, pp. 119–38.

by Bridgman were made upon hollow metal cylinders, while Adams has interpreted his results to show that the crushing strength of granite is at least seven fold as great as has been supposed. Test blocks of Westerly (Rhode Island) granite at ordinary temperatures first began to flow with pressures of 200,000 pounds to the square inch. In a discussion of these results King says:

> No state of shearing stress in the crust of the earth due to the weights of continents and mountains can cause the collapse of the rock in the neighborhood of a small cavity. . . . . At a temperature of 550° C. supposed to exist eleven miles below the earth's surface cavities will remain open when submitted to considerably greater pressures than are found at this depth.[1]

Though applying to forces whose continuance of application is short (six hours), many lines of evidence confirm the assumption of the great rigidity of the earth's crust—much the most exact as well as the most recent being the determination by Michelson that in this respect it exceeds solid steel.[2]

Recent unpublished experiments by Bridgman have an important bearing upon this point. I am permitted to quote the following from a personal letter:

> I have recently made a few experiments which show that at least for some substances the viscosity increases enormously with increasing pressure. The effect may certainly be as great as two hundred times for an increase of 1,000 atmospheres, and increases at least as rapidly as the square of the pressure.

Hayford's negative argument in favor of isostasy has thus upon the basis of later work been shown to be fallacious. In his official monographs he has supplied what he considers conclusive positive evidence in support of his contention that isostatic compensation is nearly perfect at a depth of 76 miles below sea-level—in other words, that elevations above the surface persist only by virtue of a deficiency of mass, and that basins are situated above a basement of exceptional density. Upon his hypothesis the quantity of matter is the same in all vertical columns of the same cross-section and limited below at the assumed depth below sea-level of 76 miles. This "positive" argument rests, however, upon Pratt's hypothesis, and implies a weak and failing earth shell.

[1] *Op. cit.*, p. 137.

[2] A. A. Michelson, "Preliminary Results of Measurements of the Rigidity of the Earth," *Jour. Geol.*, XXII (1914), 97–130.

His positive argument and the facts upon which it is based.—Hayford's earlier studies have dealt with the well-known differences between the astronomic and the geodetic determinations of latitude, longitude, and azimuth—so-called deflections of the vertical—measured first at 267 stations, and in a supplementary study at 116 stations, making in all 383, which are fairly well distributed over the domain of the United States. These uncorrected residuals have values which when expressed in terms of astronomic minus geodetic determination (A–G) range between $-26''.50$ and $+32''.43$, the average being, however, comparatively small. The later monographs have dealt with pendulum determinations of gravity, made at 89 stations in the first study and 35[1] in the second, a total of 124. Unfortunately, instead of correcting the measurements of gravity so as to take account of both altitude and topography and obtain a comparison of observed and computed values, Hayford has combined with the correction for topography one for "compensation" with reference to the assumed limiting surface at a depth of 76 miles below sea-level. Fact and theory have thus been combined in his tables in such a way as to make it impossible to extricate the figures representing the anomalies of gravity at each station *except upon the Pratt-Hayford hypothesis*. We are thus thrown back upon those earlier studies which deal with deflection of the vertical.

HAYFORD'S FUNDAMENTAL ASSUMPTION CONCERNING THE DISTRIBUTION OF MASS WITHIN THE EARTH'S SURFACE-SHELL

Lack of knowledge concerning distribution of mass beneath the earth's surface.—If we assume, as Hayford has done in conformity with the usual conception, that the differences between geodetic and astronomic locations of station are a measure of the horizontal components of the earth's gravitation at the station, these differences must be assumed to be made up of the horizontal components of the pulls from all elementary volumes of the earth when multiplied by mass and divided by the square of the distance from the station. But next to nothing is known concerning the distribution of density within the lithosphere. As Gilbert has said, "The inner earth is the inalienable playground of the imagination."

[1] By Bowie alone.

Preponderant effect of near masses due to law of inverse squares.—It is a direct consequence of the law of inverse squares that bodies relatively near the station exert a preponderant influence upon the intensity of gravity, and a relatively small mass of high density within a few miles of the station may thus be responsible for the major portion of the anomaly in the direction or intensity of gravity. To employ an illustration from the field about a magnetic needle: the local variation in the pointing of the needle may be explained either, upon the one hand, by the location of the station with reference to the magnetic poles of the earth, or, upon the other, by the propinquity of excessively magnetic masses—such, for example, as a deposit of magnetic iron ore. Within the Mississippi plain we find generally "normal" conditions explainable by the position of stations with reference to magnetic poles; whereas in many areas of the northern peninsula of Michigan the notable magnetic "anomaly" is explainable almost entirely by local conditions.

It has sometimes been claimed that the extension of Clairaut's theorem by Stokes makes the value of Δg. independent of local (that is, near-by) variations in density, which may be both large and abrupt. This, however, is not the case. The non-permissibility of such variations for the application of the theorem was recognized by Stokes[1], as it has been by Rudzki.[2] Clairaut in fact developed the theorem to apply to an earth supposed to have a liquid interior.

Hayford's explanation of anomalies found in systematic regularity as contrasted with local irregularity in distribution of mass.—Hayford's studies of the deflection of the vertical and of gravity irregularities within the United States have been carried out upon the assumption that they are explainable by general, as contrasted with local, conditions; and his method of reducing residuals falls in with the explanation of magnetic variation within the Mississippi plain. A solution of the problem of anomalies in the intensity of terrestrial magnetism in northern Michigan which caused these residuals to disappear through a process of general averaging would constitute a proof, not of the certitude of the hypothesis assumed, but rather of its falsity.

[1] *Mathematical and Physical Papers*, II, 164.

[2] *Physik der Erde*, pp. 35–36.

The earth's density as a whole being more than double that of the part known to us from observation, we may assume almost any distribution of matter which arranges the concentric shells in inverse order of density from the center to the surface. It is in fact quite as probable that near the surface contacts between successive shells of different density are abrupt as it is that they are gradual. Hayford has assumed, though he does not appear to regard it as an assumption of importance, that down to a depth of 76 miles (122 km.)[1] no shell of notably higher density than that at the surface is encountered. It is, however, entirely within the realm of probability that material in all respects resembling the stone meteorites or stone-iron meteorites may be found within this depth. If, further, the surface of contact between a lower shell of higher density and a higher shell of lower density is not only abrupt but irregular and characterized by notable local prominences, an explanation can be found for most local anomalies of gravity.

EVIDENCE OF LOCAL IRREGULARITIES IN DISTRIBUTION OF GRAVITY AND MAGNETIC CONSTANTS

Evidence from Russia and from Southern Italy.—It is proposed now to state certain evidences that local conditions may be responsible for large anomalies in the value of gravity. The evidence now upon record has been drawn from a number of widely separated provinces, in all of which extended series of measurements either of gravity or of deflection of the plumb line have been carried out.[2] The great plain of Russia is of special interest in a discussion of isostasy, since any anomalies in gravity which occur do not require

[1] Helmert has distinctly recognized that there are anomalies of gravity not explainable on general conditions, but, using the same assumption of the truth of Pratt's hypothesis, he has determined the depth of the *Ausgleichfläche* to be 118 ± 22 km. He has chosen for this purpose the zones of special disturbance above and on either side of the steep slope bordering the continental shelves (F. R. Helmert, "Die Tiefe der Ausgleichfläche der Prattschen Hypothese für das Gleichgewicht der Erdkruste und den Verlauf der Schwerestörung vom Innern der Kontinente und Ozeane nach den Küsten," *Sitzungsber. d. k. preuss. Akad. d. Siss. z. Berlin*, 1909, pp. 1192–98).

[2] F. de Montessus de Ballore, "Sur les anomalies de la pésanteur dans certains régions instables," *Comptes Rendus de l'Académie Française*, CXXXVI (Paris, 1903), 705–7.

large corrections for topography. It has been found, however, that in the great triangle Kamiensk-Podolsk, Kazan, Astrakhan, which relatively to the surrounding country is very unstable in a seismic sense and is bordered by dislocations, the measurements of gravity made by General Stebnitzki[1] have shown a notable deficit of gravity to characterize this marginal zone. A like threefold correspondence of seismic instability, of zones of dislocation, and of abnormal gravity has been proved for a number of other regions, notably Southern Italy and Sicily,[2] the Indo-Gangetic plain to the southward of the great protuberance of the Himalayan Highland, the North German plain, and a district in Hungary.

Evidence from India.—As the Russian province is of interest because the topographic correction is small, so the Indo-Gangetic plain at the southern base of the Himalayas offers a contrasted set of conditions and presents the best possible opportunity for testing the influence upon deflection constants of a huge protuberance of the lithosphere whose volume and probable density may be subjected to computation. It is thus of interest to find that Colonel Burrard[3] is led to ascribe the deficit of gravity in the Indo-Gangetic plain to the known zone of dislocation in correspondence with the zone of seismic instability; his view being that a great rift in the *subcrust* filled with material of low density extends to considerable depths beneath this zone.

Colonel Burrard is exceedingly favorable to the Pratt-Hayford conception of isostasy and has made computations based upon Hayford's earliest figures for the surface of compensation, yet he does not find that the residuals are thereby decreased, but, on the contrary, that they are enhanced. For the entire distance of 25 miles separating Kurseong in the outer Himalayas and Jalpaiguri

[1] M. A. de Lapparent, "Sur la signification géologique des anomalies de la gravité," *ibid.*, CXXXVII (1903), 827–31.

[2] Annibale Riccò, "Determinatione della gravità relativa in 43 luoghi della Sicilia orientale, della eolie, e della Calabria," *Mem. della Soc. degli spettroscopisti Italiani*, XXXII (1903), 173–296.

[3] Col. S. G. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India* (Calcutta, 1912), pp. 1–26. See also by the same author, "The Origin of Mountains," *Geol. Mag.*, Dec. V, Vol. X (1913), pp. 385–88; and "On the Origin of the Indo-Gangetic Trough, Commonly Called the Himalayan Foredeep," *Proc. Roy. Soc.*, A, XCI (1915), 220–38.

upon the plains, the difference in deflection is 45″, instead of 26″, which it should either equal or exceed on the conception of support by rigidity without compensation, and 15″, as it must be according to Hayford's hypothesis.[1] In a separate monograph of the Indian Survey, Major Crosthwait has discussed the application of Hayford's theory to the Himalayan area and has found that whereas for the United States as a whole the mean residual is 1″.86 and for all save the western section 1″.15, for the Himalayas it is more than eight times this amount.[2] Dr. Hayden has shown that to secure compensation the depth of the equilibrium surface must be increased from Hayford's figure of 122 km. to 330 km.[3] Applied in the region where it is most crucially tested, the Hayford hypothesis thus receives less support in the facts than does the doctrine of non-compensation.[4]

Mutual relationships of abnormal gravity, abnormal earth magnetism, dislocations, and seismicity.—In at least three widely separated provinces the coincidence of anomaly of terrestrial magnetism with that of gravity, and with that of dislocation zones, has been proved by the data from official surveys. In the earthquake province of Calabria and Sicily this result has been reached by a Royal Commission under the direction of Professor Riccò.[5]

A close correspondence between anomaly of gravity and that of terrestrial magnetism has likewise been brought out to special advantage within a province in Hungary which is relatively small, but one provided with an especially large number of stations, so

[1] Burrard, *op. cit.*, p. 4. See also Sir Thomas Holland, "The Origin of the Himalayan Folding," *Geol. Mag.*, Dec. V, Vol. X (1913), pp. 167–76.

[2] Major H. L. Crosthwait, R. E., "Investigation of the Theory of Isostasy in India," *Prof. Paper No. 13, Survey of India* (Dehra Dun, 1912), pp. 1–123.

[3] H. Hayden, "Notes on the Relationship of the Himalaya to the Indo-Gangetic Plain," etc., *Geol. Surv. India*, XLIII (1913), 138–67, Pls. 3, 4.

[4] The stations discussed by Bowie from the Indian district to indicate harmony with the Hayford doctrine are far removed from the Himalayas (W. Bowie, "Isostasy in India," *Jour. Wash. Acad. Sci.*, IV [1914], 245–49.)

[5] A. Riccò, "Anomalie del magnetismo terrestre in relatione alle anomalie della gravità nella Sicilia orientale," *Boll. dell' Accad. Gioenea di Scienze Naturali in Catania*, Fasc. 80 (1904), pp. 1–3. See also "Anomalie della gravità e del magnetismo terrestre in Calabria e Sicilia," *Annali dell Ufficio Centrale Meteorologico e Geodinamico Italiano*, XIX (1897; separate printed at Rome in 1907), 1–10, plate; also, "Anomalie della gravità e del magnetismo terrestre in Calabria e Sicilia in relatione alla costituzione del suelo, *Boll. della Soc. Sism. Ital.*, XII (1907), 393–407.

that the lines of equal anomaly of gravity have been drawn for each millimeter of acceleration.[1] The sharp changes—steep gradients—upon the map thus come into prominence, and these show very close correspondence with strong abnormality of the magnetic forces and with the intensity of earthquakes, the seismicity of the province having been investigated by Rethly.[2]

For the area of the North German plain, Deecke, making use of data upon magnetic constants determined by Schück and of those of gravity issued by Helmert from the Royal Prussian Geodetic Institute at Potsdam, has shown that the lines of equal anomaly of gravity correspond closely with those of terrestrial magnetism (involving both inclination and declination), and that these lines are further, in many cases, those of recent faulting, and in some cases were probably the seats of movement during the earthquake of October 23, 1904.[3] In this connection it is of interest that a resurvey of magnetic elements in Japan subsequent to the great earthquake of 1891 indicated remarkable changes in the isomagnetics of the province.[4]

In connection with a general survey of geodetic data assembled from many regions, Helmert, though approving Hayford's views, has concluded that gravity values are in many localities not completely in harmony with Pratt's hypothesis,[5] and that this is especially true for the oceanic islands, for the margins of the continental

[1] Baron Roland Eötvös, "Bestimmung der Gradienten der Schwerkraft und ihrer Niveauflächen mit Hülfe der Drehwage," *Abh. der XV. Allgemeinen Konferenz der Erdmessung in Budapest, 1906*, I, 1–59 (reprint). See also, by the same author, "Über Arbeiten mit der Drehwage ausgeführt im Auftrage der königlichen ungarischen Regierung in den Jahren 1909–1911," *Bericht an die XVII. Allgemeine Konferenz der Internationalen Erdmessung* (Budapest, 1912), pp. 1–17.

[2] *Földrajzi Közlemenyek*, XXXIX, 391–420.

[3] W. Deecke, "Erdmagnetismus und Schwere in ihrem Zusammenhange mit dem geologischen Bau von Pommern and dessen Nachbargebieten," *Neues Jahrb. f. Mineral.*, etc., Beilage Bd. 22 (1906), pp. 114–38, Pls. 1–3.

[4] D. Kikuchi, *Jour. Coll. Sci. Univ. Tokyo*, V, 149–92.

[5] Wenn Pratts Hypothese erfüllt ist, so müssen sich die Schwerestörungen Δg. lediglich aus Höhenstörungen der Massenlagerung über der Ausgleichsfläche erklären lassen. Dies gelingt aber nicht völlig; man muss daher auch noch Horizontalverschiebungen annehmen, welche die Massenlagerung gestört haben. Es treten sogar ausgedehnte Massenstörungen auf, wo die sich gegenseitig ausgleichenden Massen nicht erkennbar sind, so dass man nur schlechthin von Anhaüfungen und Defekten sprechen kann, die sich also als erhebliche Abweichungen von Pratts Hypothese darstellen" (*Sitzungsber. Berliner Akad. d. Wiss.* [II, 1908], 1060).

shelves, for mountain summits, and for intermontane valleys. He gives, as the most noteworthy of aberrant districts, Hawaii, Corsica, Sicily and Calabria, the Austrian Alps and the Carpathians, large areas in Turkestan continued eastward to the Pamirs, Lake Baikal, and localities within the valley of the Obi River in Siberia. These, with the exception of the one last mentioned, from which few seismic data are available, are notably the great earthquake zones of the Eastern Hemisphere.[1]

HAYFORD'S FIGURES ANALYZED WITH THE IDEA OF COMPENSATION ELIMINATED

Deflections corrected for topography to find attraction of hidden masses.—We have thus seen that in many regions the evidence favors the view that anomaly of gravity is connected with local irregularity and not alone with general and orderly—systematic—distribution of mass over a wide area. Hayford's gratuitous assumption has been that the distribution of mass which produces gravity anomaly (Δg.) is throughout regular and systematic; and to this he has added the additional assumption of a failing earth, which in the light of recent work does not appear to be well founded. Pratt's hypothesis of compensation was designed to meet conditions within an earth shell of supposed high plasticity, and Hayford has contributed to this theory a determination of the supposed depth of the compensation surface. His assumed proof has consisted in testing by the method of least squares a number of hypothetical *systematic* distributions of matter in the unknown region, with the use of the measurements of deflection of the vertical and of gravity within the area of the United States. His choice of the depth of 76 miles for complete compensation was based upon a reduction of the sum of the squares of the residuals to about one-tenth of that obtained upon the hypothesis of a rigid earth *without important local irregularities in distribution of matter.*

If it be true that local anomaly is to be ascribed largely to irregular local distribution of mass beneath and near the station, Hayford's method is inapplicable and can only lead to erroneous results.

[1] Cf. de Montessus, "Les tremblements de Terre," *Géographie Séismologique* (Paris, 1906), Map 1.

Let us then see from examination of his figures whether they betray evidence of large local as against broad systematic distribution only of the concealed matter beneath and about the station. For reasons already given, this test of his figures is possible only in case of the deflections of the vertical.

Distribution of residuals in excess of 50″ *of arc.*—Hayford has computed with considerable care the topographic deflections for each station, and this resultant horizontal pull of the *determinable* masses at the station, when deducted from the measured deflection, must leave a residual fixed by the *hidden* masses whose distribution of density is unknown. By assembling his topographic corrections and applying them we obtain residual deflections which range from zero to 89″.46 of arc.[1] We have arbitrarily selected in a first survey of the results an arc of 50″, or something more than half the maximum residual, as a *minimum of excessive anomaly* in order to determine the plan of distribution. The results are shown in Table I.

Thus it is seen that 100 stations out of a total of 774 (numbering stations separately for latitude and for longitude or azimuth) gave residuals, after correction for known distribution of matter, which are in excess of 50″ of arc. These constitute 12.9 per cent, or about one-eighth of the entire number, and it is a fact of much significance that, with the exception of two stations which are

[1] We may here ignore the sign of the residual deflection, which indicates the direction of displacement of the zenith. The topographic correction is for the coastal regions particularly large and often several times the measured deflection. It is therefore interesting to find that the uncorrected deflections are also in the Pacific coastal region the largest for the United States. Deflections of the vertical for the entire series of Hayford which are in excess of 15″ are the following, with station numbers given:

In meridian: 238, Santa Barbara (−18.38); 245, Los Angeles (−17.99); 364, Mt. Wilson (−28.50).

Prime vertical: 1, Point Arenas (+16.98); 224, Tepusquet (+20.15); 225, Arguello (+15.90); 227, New San Miguel (+20.62); 228, Santa Cruz W. (+19.71); 229, Santa Barbara (+15.04); 230, Los Angeles N.W. (+19.56); 231, Los Angeles S.E. (+21.55); 236, Sulphur Pk. (+18.82); 237, Ross Mt. (+18.18); 241, Avila (+29.93); 242, San Buenaventura (+19.38); 244, Soledad (+28.06); 245, San Diego (+32.43); 23, Genoa (−18.65); 42, Ogden (+16.25); 43, Waddoup (+24.84); 44, Salt Lake City, Long. Sta. (+15.37); 45, Salt Lake City, Az. Sta. (+18.15); 46, Mt. Nebo (+18.69); 61, Colorado Springs (−18.74).

TABLE I

"ABNORMAL" DEFLECTIONS OF THE VERTICAL—HAYFORD (CORRECTED FOR TOPOGRAPHY)

(Minimum, 50″ of Arc)

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN MERIDIAN			
233	Mt. Toro	36°32′	121°37′	52.″34
234	Arguello	34 35	120 34	53.97
236	Santa Cruz W	34 4	119 55	56.62
237	New San Miguel	34 2	120 23	55.30
242	Lospe	34 54	120 36	51.08
246	Dominguez Hill	32 52	118 14	59.03
254	Point Pinos	36 38	121 56	51.00
260	San Luis Obispo	35 11	120 45	52.41
261	Avila	35 11	120 43	50.22
264	San Buenaventura	34 16	119 16	53.29
265	San Pedro	33 43	118 17	58.61
266	Santa Catalina	33 26	118 30	57.90
267	Soledad	32 50	117 15	50.04
361	Harbor	33	118 34	54.22
362	Wilson Peak	34 13	118 3	50.50
363	Los Angeles N.W	33 55	118 3	53.98
	DEFLECTIONS IN PRIME VERTICAL (LONGITUDE)			
1	Point Arena	38 55	123 41	87.65
3	Ukiah	39 9	123 12	81.84
6	New Presidio	37 48	122 27	79.47
7	Lafayette Park	37 48	122 26	80.34
8	Washington Square	37 48	122 25	80.26
9	Mt. Hamilton	37 21	121 38	77.84
10	Marysville	39 8	121 35	75.75
16	Sacramento	38 35	121 30	75.07
246	San Diego 1871	32 43	117 9	62.49
20	Lake Tahoe S.E	38 57	119 57	70.88
22	Verdi	39 31	119 59	66.21
23	Genoa	39	119 51	71.66
24	Carson City	39 10	119 46	62.26
25	Virginia City	39 19	119 39	59.71
216	San Diego	32 43	117 9	63.69
217	Los Angeles Normal Sch. 001	34 3	118 15	61.52
243	Buenavista	34 3	118 15	61.26
352	Wilson Peak	34 13	118 3	61.22
353	Mare Island	38 6	122 16	75.54
361	Gazelle	41 32	122 31	75.50
367	Eugene	44 4	123 5	77.72
372	Portland	45 31	122 41	63.58
376	Tacoma	47 16	122 27	57.98
377	Seattle, 1908	47 40	122 19	57.79
378	Seattle, 1888	47 37	122 20	58.77
381	Port Townsend	48 7	122 45	60.71
382	Blaine	48 59	122 45	50.95

TABLE I—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)			
2	Paxton	39° 8′	123°19′	78.″79
4	Mt. Helena	38 40	122 38	66.59
5	Mt. Tamalpais	37 55	122 36	77.95
224	Tepusquet	34 55	120 11	60.63
225	Arguello	34 35	120 34	70.19
226	Gaviota	34 30	120 12	63.38
227	New San Miguel	34 2	120 23	59.65
228	Santa Cruz W	34 4	119 55	56.70
229	Santa Barbara	34 24	119 43	58.71
234	Dominguez Hill	33 52	118 14	58.01
236	Sulphur Peak	38 46	122 51	66.37
237	Ross Mountain	38 30	123 7	72.48
238	Point Avisadero	37 44	122 22	88.84
239	Monterey Bay	36 36	121 53	89.46
240	Santa Cruz	36 59	122 3	73.20
241	Avila	35 11	120 43	54.51
242	San Buenaventura	34 16	119 16	52.56
221	Santa Lucia	36 9	121 25	81.74
222	Castle Mount	35 56	120 20	65.75
223	Lospe	34 54	120 36	71.71
11	Monticello	38 40	122 11	72.19
12	Vaca	38 23	122 5	74.89
13	Mt. Diablo	37 53	121 55	75.38
14	Yolo, N.W. Base	38 41	121 51	68.34
15	Yolo, S.E. Base	38 32	121 48	69.97
17	Mocho	37 29	121 33	77.15
18	Mt. Lola	39 26	120 22	75.44
19	Round Top	38 40	120	74.44
21	Lake Tahoe S.E.	38 58	119 57	63.96
26	Mt. Conness	37 58	119 19	66.91
27	Carson Sink	39 35	118 14	60.49
218	Santa Ana	36 54	121 14	72.64
219	Mt. Toro	36 32	121 37	78.97
220	Hepsedam	36 19	120 49	65.71
111	Cape Henry Lighthouse (old)	36 56	76 1	52.72
116	Wolftrap	37 24	76 15	51.02
351	Harbor	33	118 34	72.60
354	Snow Mountain E.	39 23	122 45	81.50
355	Marysville Butte	39 12	121 49	82.51
356	Mt. Grant	38 34	118 47	61.80
357	Kent	39 58	122 44	81.52
358	Lyons	40 18	121 38	77.35
359	Round	40 48	121 57	77.95
362	Rust	42 37	122 21	75.06
363	Onion	42 41	123 14	85.05
364	Scott	43 22	123 4	85.76
365	Spencer	43 59	123 6	81.06
368	Mary	44 30	123 33	76.64
369	Yam	45 4	123 9	76.15
370	Barnes	45 32	122 45	63.31

TABLE I—*Continued*

DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
371.....	Balch.....	45°32′	122°43′	63″70
373.....	Lam.....	46 8	122 28	68.56
374.....	Bel.....	46 47	121 56	59.78
379.....	Point Hudson.....	48 7	122 45	66.69
389.....	Classet.....	48 23	124 40	52.32
390.....	Beechy Head.....	48 20	123 39	56.69

located in the Atlantic Coast province (see below, p. 711), all are to be found within the intense seismic area of the Pacific coastal region, which was so recently, after the destructive California earthquake of 1906, the subject of special investigation. When now the stations showing notable anomaly are accurately plotted upon the special map of the seismic province prepared by the Earthquake Investigation Committee,[1] it at once appears that there is an apparent relationship between their distribution and that of the better-known recent faults of the province. The number of stations with corrected anomaly of deflection greater than 50″ is something more than half (58 per cent) of the total number of stations within the Pacific Coast province. In the map of Fig. 1 which shows the distribution of the abnormal stations (in dotted outlines the map of the Earthquake Investigation Committee) black circles of different diameters have been used to bring out roughly the magnitude of the corrected residuals, and it appears that those of higher order particularly are generally grouped near the known displacements of the district, some of which have been the seats of movement during recent earthquakes.[2]

Distribution of residuals in excess of 35″ of arc.—Had the minimum of abnormality of deflection been made 35″ of arc, instead of

[1] A. C. Lawson, G. K. Gilbert, H. F. Reid, J. C. Branner, A. O. Leuschner, George Davidson, Charles Burckhalter, and W. W. Campbell, *Atlas of Maps and Seismograms* accompanying the *Report of the State Earthquake Investigation Committee upon the California Earthquake of April 18, 1906* (Carnegie Institution of Washington, 1908), Map 1.

[2] The recent faults are not indicated on the area outside the dotted border. Few gravity data relatively are available for the area east of California, where many fault lines are shown.

50″, practically all of the remaining stations located within the California earthquake province would have been included, and a separate group would have been found within the Atlantic coastal

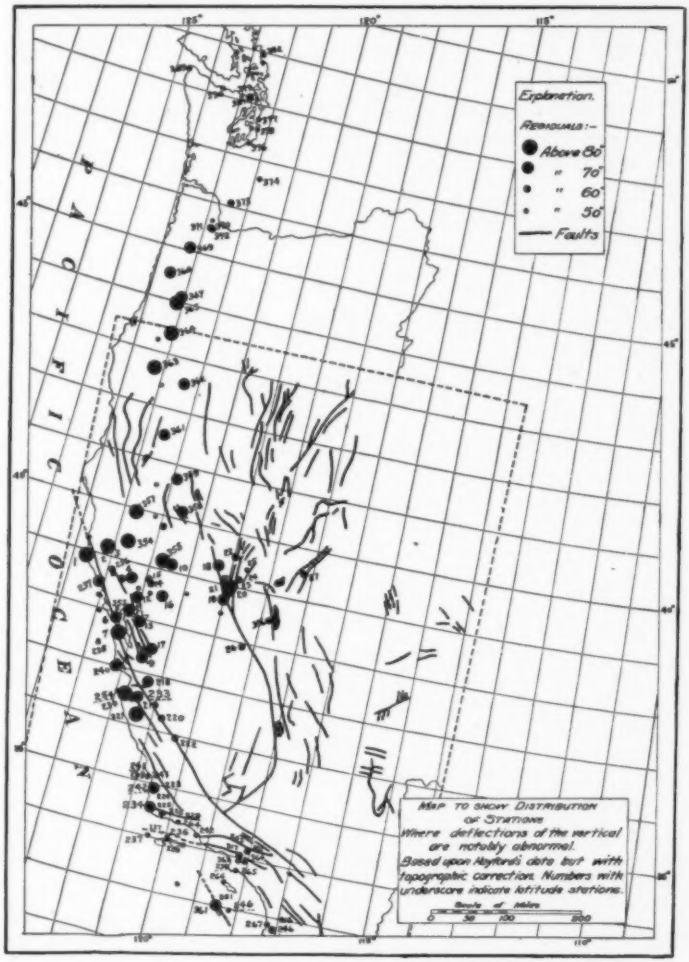

FIG. 1

province (Hayford's northeastern and southeastern groups of stations). This supplementary list prepared upon the basis of a minimum of abnormality of 35″ of arc, but without including the additional Pacific slope stations, is given in Table II, following.

The stations listed in this table have been plotted and appear in the map of Fig. 2 with some indication of the measure of abnormality, and upon the map of Fig. 3 are found the points of higher seismicity as determined by De Montessus upon the basis of recorded data,[1] which, however, of necessity give undue prominence to localities of early settlement or of later importance commercially.

General conclusion as to law of distribution of anomaly of gravity.—Hayford's own observations thus confirm the evidence derived from other regions that anomaly of deflection of the vertical and of gravity show large local defect or excess, and that these local anomalies are in some way connected with the distribution of seismicity and with zones of dislocation.[2] We believe therefore that the late Professor de Lapparent was correct when in 1903 he stated with much force before the French Academy:

> I believe, therefore, that for the present we may claim that the sea upon the one hand, and the continents upon the other, enter into the variations of gravity there only where a dislocation puts into contact two crustal compartments, one of which is depressed and one of which remains stationary or is fixed. . . . .
>
> One may add that even in countries where the surface does not reveal the dislocations, a means is found for diagnosing the deep and hidden faults. Finally, the relation of seismic regions to rapid variations in the anomaly of gravity shows that it would be eminently proper to carry out such studies in order to make known those provinces of our globe which have most to reckon with the danger from earthquakes [translation].[3]

May not the truth, as in so many other controverted questions, lie between the extreme viewpoints? It is possible to assume

[1] Count F. de Montessus de Ballore, "Les Etats Unis séismiques," *Archives des Sciences Physiques et Naturelles de Génève*, 4th period, V (1898), 201–16. See also William H. Hobbs, "On Some Principles of Seismic Geology," *Gerlands Beiträge zur Geophysik*, VIII (1907), Appendix, pp. 289–92, Pl. 2; also, *Earthquakes* (Appleton, 1907), pp. 112–16.

[2] While magnetic data are available for the territory of the United States (*United States Magnetic Tables and Magnetic Charts for 1905* [Washington, 1908]), their discussion by Bauer is still unpublished, and it would be premature to discuss them here.

[3] M. A. de Lapparent, *op. cit.*, pp. 830–31.

TABLE II

"ABNORMAL" DEFLECTIONS OF THE VERTICAL—HAYFORD (CORRECTED FOR TOPOGRAPHY) (MINIMUM, 35″ OF ARC)

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN MERIDIAN			
136	Yard	39°58′	75°23′	37″.81
137	Mt. Rose	40 22	74 43	35.22
158	Howard	44 38	67 24	37.97
164	Calais	45 11	67 17	35.97
350	Folger	41 17	70 6	38.56
	DEFLECTIONS IN PRIME VERTICAL (LONGITUDE)			
90	Charlottesville	38 2	78 31	43.20
92	Strasburg	38 59	78 22	38.42
99	Naval Observatory	38 55	77 4	37.40
100	Naval Observatory	38 54	77 3	38.28
101	C. and G.S. Observatory	38 53	77 1	35.61
108	Dover	39 9	75 31	38.69
110	Cape May	38 56	74 56	44.91
113	Roslyn	37 14	77 24	40.74
114	Staunton	38 9	79 4	39.74
118	Seaton	38 53	77	35.51
119	Statesville	35 47	80 54	36.38
157	Cambridge	42 23	71 8	41.42
158	Duxbury	42 3	70 40	42.19
172	Bangor	44 48	68 47	35.14
173	Calais	45 11	67 17	35.92
233	Provincetown	42 3	70 11	39.05
253	Kit	41 30	73 59	41.63
257	Mt. Weather	39 4	77 53	44.77
	DEFLECTIONS IN PRIME VERTICAL (AZIMUTH)			
91	Clark	38 19	78	41.78
93	Long Mount	37 17	79 5	44.99
94	Bull Run	38 53	77 42	40.30
95	Maryland Heights	39 20	77 43	41.52
96	Sugarloaf	39 16	77 24	42.61
97	Causten	38 56	77 4	35.32
109	Cape Henlopen	38 47	75 5	46.63
111	Cape Henry	36 56	76 1	52.72
115	Knott Island, North End	36 34	75 55	47.68
116	Wolftrap	37 24	76 15	51.02
117	Tangier Island	37 48	75 59	42.32
120	Moore	36 24	80 17	37.72
122	King	35 12	81 19	35.29
142	Yard	39 58	75 23	42.26
143	Mt. Rose	40 22	74 43	46.12
144	Beacon Hill	40 22	74 14	42.50
147	Cambridge	42 23	71 8	38.24

TABLE II—*Continued*

Station No.	Station Name	Lat. (N.)	Long. (W.)	Deflection (Corrected)
	DEFLECTIONS IN PRIME VERTICAL (ASIMUTH)—*Continued*			
149.....	Spencer.....	41°41′	71°30′	45″.30
150.....	Beaconpole.....	42	71 27	43.38
151.....	Copecut.....	41 43	71 4	40.10
152.....	Indian.....	41 26	70 41	46.49
153.....	Shootflying.....	41 41	70 21	37.97
154.....	Blue Hill.....	42 13	71 7	41.90
156.....	Thompson.....	42 37	70 44	40.35
159.....	Unkonoonuc.....	42 59	71 35	37.98
161.....	Agamenticus.....	43 13	70 42	41.42
235.....	Davis.....	38 20	75 6	48.87
248.....	Mt. Blue.....	44 44	70 31	37.15
254.....	Gardiners Island.....	41 6	72 6	37.42
255.....	Barnegat Inlet.....	39 46	74 6	40.78
258.....	Cahas.....	37 7	80 1	38.07
338.....	Chapel Hill.....	40 24	74 4	44.23
383.....	Sankaty Head.....	41 17	69 58	37.71
384.....	High Point.....	41 19	74 40	40.99
385.....	Womelsdorf.....	40 19	76 12	40.98

that a tendency to attain to isostatic adjustment exists within the earth's outer shell as a consequence of diastrophic action, and that at any given time large areas, such as the greater portion of the United States, are measurably compensated. In areas more recently disturbed and at a more rapid rate (western section of the United States or the Himalaya region), which still betray their lack of stability in earthquakes, no such state of isostatic compensation can be postulated. Such regions show a rigidity sufficient to support their excessive loads for long periods even if measured in geological units, and if they yield to some extent through eventual fatigue of the materials under strain, this effect lags far behind the degrading effects of surface erosion and transportation. Some suggestion of this idea appears to be found in the paper by Crosthwait.[1]

CRITICISM OF HECKER'S DETERMINATIONS OF GRAVITY OVER THE OPEN SEA

Helmert's claim that gravity is nearly constant over deep water of the ocean.—A line of evidence which has been held to support the conception of isostatic compensation, but for the oceanic areas

[1] *Op. cit.*, pp. 4–5.

only, is that supplied by Helmert and Hecker, who have applied the Mohn hypsometer-barometer to measurements of gravity over the open sea. Upon the basis of these studies, which were executed

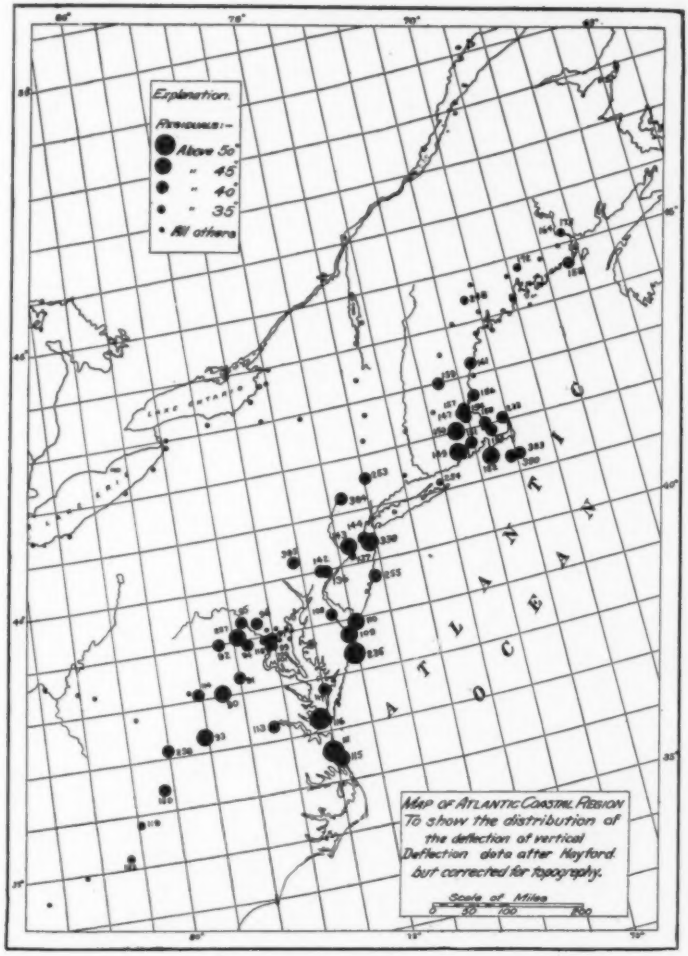

FIG. 2

by Hecker, Helmert has claimed that "the force of gravity above the deep water of the Atlantic Ocean between Lisbon and Bahia is nearly normal"—that is to say, the same as at the shore within

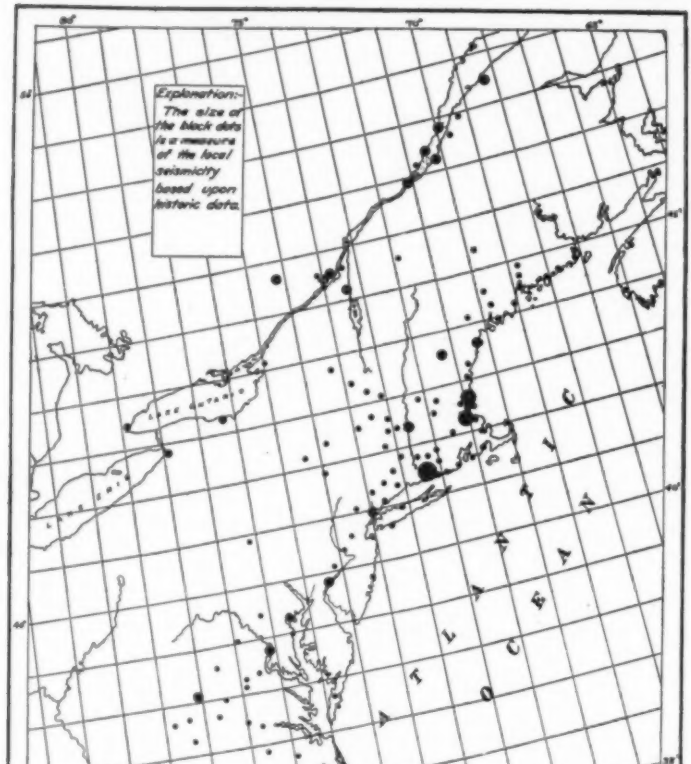
Explanation:-
The size of the black dots is a measure of the local seismicity based upon historic data.
ATLANTIC
OCEAN
Map of Atlantic Coastal Region
To show the distribution of seismicity.
Seismic data after de Montessus.
Scale of Miles
0 200 400

FIG. 3

the same latitude.[1] If this statement is well founded, it would be difficult to escape the conclusion that at least partial compensation exists for the oceanic areas. But from examination of the figures in Hecker's original monograph,[2] a different form of statement would seem better to express the facts. Up to the time of Hecker's Atlantic voyage geodesists, through basing their conclusions upon pendulum observations made upon a few oceanic islands, had held the belief that gravity is uniformly in excess over the oceans; and the force of Helmert's statement lay in the fact that it exploded this notion, which had received official sanction from an international geodetic congress. A better form of statement would appear to have been that Hecker's results did not in general reveal the high excess above normal values which had been expected. But values of Δg. which range from 146 units[3] of defect to 161 units of excess can hardly be called nearly constant unless errors of measurement be assumed to be excessive.

Hecker's grouping of his data objectionable in that it tends to efface significant local anomalies.—Hecker's paper is open to the objection that by a process of averaging the local significance of Δg. is made largely to disappear. Of this, two examples will suffice: the first, of measurements made over the shallow North Sea and British Channel with depths ranging from 60 to 160 meters only; and the second, a group of four measurements made between the Cape Verde Islands and the equatorial ridge over unknown but presumably large depths, which from a few not very distant soundings are probably generally in excess of 5,000 meters (Tables III and IV).

Hecker's revision of his data after the Black Sea cruise.—The figures as first published by Hecker were shown by Baron Eötvös to need correction for direction of motion of the vessel (west or east), and after having tested the magnitude of this correction in a special

[1] F. R. Helmert, "Dr. Heckers Bestimmung der Schwerkraft auf dem atlantischen Ozean," *Sitzungsber. d.k. preuss. Akad. d. Wiss. z. Berlin*, I (1902), 126–28.

[2] O. Hecker, "Bestimmung der Schwerkraft auf dem atlantischen Ozean, sowie in Rio de Janeiro, Lissabon und Madrid, *Veröffentlichung d. k. preuss. Geod. Inst.* (N.F.), No. 11 (Berlin, 1903), pp. 84–85, Pl. 6.

[3] Measured in thousandths of a centimeter of acceleration.

cruise over the Black Sea, Hecker has now so revised his figures that they are no longer recognizable, and many of the excessive values for Δg. for one reason or another have disappeared altogether.[1] This is true, for example, for the third entry in the list quoted in table III. Hecker's methods have been more sharply challenged by Bauer[2] upon the ground that his instruments were

TABLE III

NORTH SEA AND BRITISH CHANNEL

Lat.	Long.	Δg. in cm.	Hecker's Mean
51°25′N.	3°50′E.	+0.053	−0.015
51 25 N.	3 40 E.	+0.016 (0.134)*	
49 58 N.	1 1 W.	−0.118	
49 50 N.	1 17 W.	−0.035	
49 45 N.	2 29 W.	0.000	
49 39 N.	2 45 W.	−0.067	

*Author's interpolation.

TABLE IV

BETWEEN CAPE VERDE ISLANDS AND EQUATORIAL RIDGE

Lat.	Long.	Δg. in cm.	Hecker's Mean
11°52′ N.	26°57′ W.	−0.065	−0.038
11 44 N.	36 59 W.	−0.146 (0.189)*	
10 54 N.	27 21 W.	+0.043	
10 44 N.	27 55 W.	+0.017	

*Author's interpolation.

not sufficiently standardized and checked during the work, and because his methods were in other respects open to criticism. In his first paper Bauer has sought further to discredit Hecker's corrected figures upon the ground that the values for Δg. vary more widely from Hayford's than did those of the first series. This point of view is interesting as indicating that local anomalies in

[1] O. Hecker, "Bestimmung der Schwerkraft auf dem schwarzen Meere sowie neue Ausgleichung der Schwerkraftmessungen auf dem atlantischen, indischen und groszen Ozeane," *Veröffentl. d. Zentralbureaus d. Internationalen Erdmessung* (N.F.), No. 20 (Berlin, 1910), pp. 1–160, 4 pls. (especially pp. 151–60).

[2] L. A. Bauer, "On gravity determinations," etc., *Am. Jour. Sci.* (4), XXXI (1911), 1–18. See also Hecker's remarks on "Ocean Gravity Observations" (a reply to Hecker), *ibid.*, XXXIII (1912), 245–48.

gravity must be forced out of sight or be interpreted by specialists in the field of the exact sciences as evidence of inaccurate work.

Hecker's figures in general indicate large anomalies of gravity above submerged escarpments and near where seaquakes have been felt.—If it be assumed that the limit of error in Hecker's measurements is not too high, his data from the Atlantic (the earlier ones particularly) and from the Indian and Pacific oceans all show a maximum of anomaly above the steep slopes at the margins of the continental shelves, and in general above submerged escarpments. Examined with reference to recorded seaquakes the earlier data in particular are hardly less interesting. Above the escarpment off the mouth of the Tagus, where such excessive values were recorded, it is known that several ships received heavy shocks at the time of the Lisbon earthquake (Fig. 4). The measurement of 0.146 of defect in the British channel, where there is no visible evidence for defect of matter (this figure had nearly disappeared in the earlier table under the mean of 0.015, and had vanished completely from the later tables), is almost exactly above the spot at which a seaquake has been put on record by Rudolph[1]—the only recorded one upon his map within a radius of 500 miles. Other noteworthy correspondences between seismicity and abnormal gravity will be noticed upon comparing Hecker's figures with Rudolph's map.

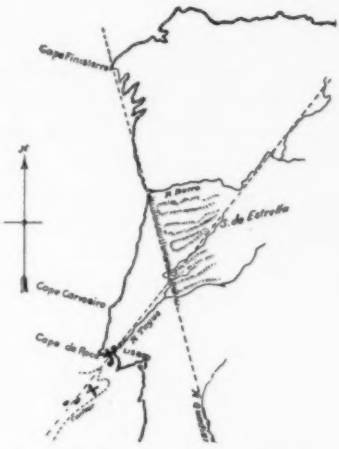

FIG. 4.—Sketch map of a portion of the Iberian Peninsula to indicate the great lineament of the Tagus, along which shocks were especially heavy at the time of the Lisbon earthquake of 1755. The positions of ships which felt the shock of the Lisbon earthquake are indicated, and also the two positions (crosses) where Hecker's measurements showed excessive values.

UNIVERSITY OF MICHIGAN
January, 1916

[1] E. Rudolph, "Über submarine Erdbeben und Eruptionen, mit Tafel iv–vii," *Gerlands Beiträge zur Geophysik*, I (1887), 133–365 (map at end).

A STAGE ATTACHMENT FOR THE METALLOGRAPHIC MICROSCOPE

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A device to obviate the necessity of mounting specimens that have been polished on one side only has been found very convenient by the writer. It consists of a disk of brass with a hole about three-eighths of an inch in diameter at the center. The lower surface is plane and the upper side is turned to an inverted conical surface, shown in plan and elevation at *D* in Fig. 1. The disk is fitted into the stage aperture, where it may be held by a steep pitch screw, in which case the outer edge of the lower projection is milled. The post *P* is screwed into the stage from below, at one corner. A spring *S* is attached to a brass block, held in place by a set screw. This spring supports the specimen, which is placed with its polished surface against the lower side of the disk. The spring pressure is controlled by the position of the block. The upper side of the disk is cut away to allow the objective to come to its focal distance from the surface to be examined. The plane surface of the disk is perpendicular to the axis of the microscope; consequently the whole field is brought into focus at the same position, without the usual care necessary in mounting the specimen. The specimen may be moved around without loosening of the spring, except in the case of unusually irregular pieces.

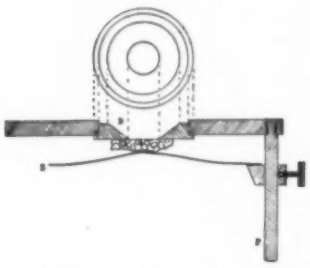

FIG. 1.—Plan and elevation of attachment.

FIG. 2.—Spring clip.

The size of the aperture depends upon the size of the specimen, but it must be large enough to permit the highest-power objective used to come to its focal distance. Where a specimen is large, a larger aperture has the advantage of exposing more of the surface to view, facilitating the finding of such features as are visible megascopically. Where the megascopic characters are of great importance, the disk may be replaced by a ring, with three converging arms attached within it. These arms have a profile like the cross section of the disk. The ring and arms must be ground to a true lower surface, and the arms must be polished to prevent scratching of soft specimens.

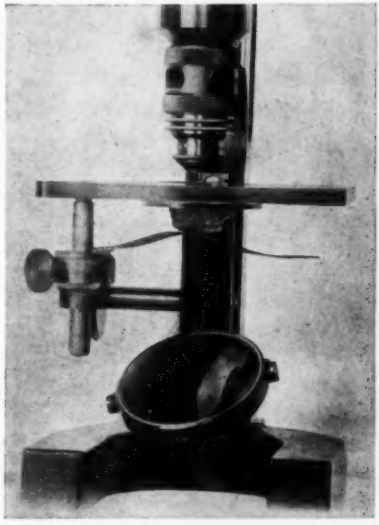

FIG. 3.—Photograph of microscope with attachment in place.

Instead of inserting the post as shown in Fig. 1, it has been found possible to use a spring clip of the form shown in Fig. 2, if the variation in the thickness of the specimens is not too great. The ends E and E' hook over the upper surface of the stage, and support the spring, which is made of thin spring brass, about one-half inch wide. If carefully fitted the disk may be forced into place, where it will stay without the necessity of threading. Using the second type of spring and the fitted disk makes the attachment very inexpensive and at the same time effective, especially if a number of springs of different curvature for different sizes of specimens are made.

It will be seen that, in addition to the fact that the necessity of mounting the specimen is eliminated, the position of the stage when in focus is the same without reference to the thickness of the specimen. This removes the necessity of stage focusing, and facilitates the work when a comparative study of two or more specimens is being made. Fig. 3 shows a microscope with the attachment as it is used.

Reviews

Geology Physical and Historical. By H. F. Cleland, Ph.D. New York: American Book Co., 1916. Pp. 718, figs. 588.

This new textbook enters the field of general geology, a field already fairly well covered by a number of excellent books. The value of this new attempt will depend upon new material, new methods of treatment, or fewer infelicities than the other books have. The book occupies in its scope a middle ground among the books on the subject, being more ambitious than some and more modest than others. It will be used properly as a textbook in first courses in general geology in colleges and universities, where the students are at least fairly well prepared and somewhat mature.

The book is about the proper length best to serve its purpose, is pleasingly written, beautifully illustrated, and well bound. The press-work is exceptionally good. The reviewer has read the book through and knows of but one typographic error. The book is printed on glossy paper, and yet it is portable and durable.

The author of the book seems to be more at home in Part II, "Historical Geology," than in Part I, dealing with physical geology. This greater familiarity with the last portion of his subject is reflected in better English, more careful treatment, more detail, and greater accuracy and definiteness in Part II than in Part I. The best part of the book is that dealing with life, although some will think that this phase of geology is overdone.

There are a few glaring omissions. The origin of dolomite is avoided on p. 249. There is a chapter on earthquakes, but no presentation of the more important aspects of diastrophism, except as the subject is scattered through the chapters on structural geology, metamorphism, and mountains and plateaus. This is a weakness which is felt throughout the book. Proterozoic glaciation in Ontario, the causes of Permian glaciation, the Pleistocene Driftless Area, are not mentioned. There is no classification of the plant and animal kingdoms, an omission which depreciates the value of the excellent paleontological material in Part II.

With the exception of a few errors, such as plural nouns with singular verbs or vice versa, indefinite antecedents of pronouns, a rather free

use of "the former" and "the latter," the English is good. The author uses words denoting time where place or number is involved in a monotonously regular way. The book must contain over a thousand cases of such misused words.

The origin and derivation of technical terms introduced throughout the book is a feature of much value. This point is somewhat discounted, however, by the use of some of these terms before they have been explained. For instance, the terms "travertine," "strike," "eskers," "basal conglomerate," "feldspars," "scoriaceous," "stoping," "schistose," "systems," "fauna," "phylum," are all introduced in advance of their explanation, and some of them are used repeatedly without explanation.

The scientific and pedagogical character of the book is marred by a certain odd looseness and indefiniteness of statement, which must militate against clear thinking and expression on the part of the student. On p. 298 lava is said to be "molten" rock; on p. 300 it is made clear that lava is rock dissolved rather than melted; and on p. 329 it is stated that igneous rocks "have consolidated from a state of fusion." The first part of the last sentence on p. 253 is true only when the surface of the ground is flat or nearly so. In Part II the terms "system," "group," "period," "era," etc., are defined, but these terms are used in various ways on pp. 383, 389, 392, 401, 384, 477, and 574. On pp. 89 to 92 various points are numbered for the sake of definiteness, but points 4 and 5 are quite similar to point 1; in the same way on p. 128, 5 and 1 are practically identical. On pp. 199 and 200 there are three statements, each of which appears to be contradictory to the other two. Some of the geography is ambiguous, especially that which refers to the western portions of the United States. The author of the book does not seem to realize the magnitude and importance of the area west of the Mississippi River. An illustration is found on p. 403, where the Cambrian rocks are carefully located in the East and then are said to be exposed "in portions of the West." On p. 658 the exact meaning of the figures at the close of the second paragraph is not clear. Illustrations of this looseness and indefiniteness are found on at least thirty-three pages of the book.

Although most of the topics are treated adequately, an effort to obtain brevity has led to incomplete treatment of antecedent streams, p. 102, of tides, p. 202, of the economic importance of metamorphism, p. 351, of the Planetesimal Hypothesis, pp. 386 and 387, of the physical problems of the Ordovician, pp. 418 to 434, of the Red Beds, p. 511, of the

economic products of the Miocene, pp. 579 to 580, of the glacial and interglacial stages of the Pleistocene, pp. 648 to 651, and of other equally important topics. On the other hand, many topics are treated with unnecessary detail. The relatively unimportant subjects of geysers, cirques, icebergs, coral reefs, and earthquakes are given too much space. Throughout Part II life is given a more prominent place than physical history. The physical history of the Devonian occupies 4 pages, the life-history, 13 pages; Mesozoic stratigraphy has 15 pages; life, 48 pages; Tertiary history covers 18 pages, Tertiary life, 52 pages.

Perhaps the greatest fault of the book has to do with order. The author has seen fit to exclude separate chapters on lakes, sedimentary rocks, and diastrophism, and to scatter these important subjects through other chapters. The result is disorganization. In Part II the various life-forms are discussed as life-forms rather than as earth inhabitants at stated times in geologic history, resulting in better biologic than geologic treatment. Stream erosion and stream deposition are badly mixed (monadnocks, for instance, on p. 111 belong on p. 105), lacustrine deposits, even peat, the origin of rock salt, extinct lakes, are all discussed under the work of streams; ice in lakes, cuestas, and sedimentary rocks appear nowhere save in the chapter on the ocean; chalk is found under deep sea deposits; hinge faults are separated from other types of fault and included under earthquakes; igneous rocks are classified before minerals are referred to; Pennsylvanian coal is scattered; Cretaceous sequoias are treated in the Tertiary; on pp. 545 and 646, "1. Other Continents" and "2. North America" should be in reverse order.

On the whole, the book shows an excellent attitude toward unsettled and controversial questions. In most cases both sides are fairly stated and the reader is allowed to take either view. The author is orthodox in most of his views. Geologists, however, will tend to disagree with some of his statements, such as the origin of geodes, p. 79, the history of the Tennessee River, p. 117, and the peneplaination of the larger part of North America during the Cretaceous period, pp. 518 to 520. It is doubtful if marble weathers to calcareous clay (p. 350). On pp. 417, 437, 451, and 590 there is intimation and definite statement that climatic zones did not exist until recent stages in the history of the earth; this is easy to write but not so easy to explain. There is grave doubt whether Devonian vulcanism in New England and Nova Scotia had anything to do with Permian diastrophism in the Appalachian Mountains (p. 455). The author of the book will hardly convince the majority of geologists of the unimportance of diastrophism and the relative importance of life-

changes in stratigraphic classification and correlation, and especially of the truth of his statement on p. 582 that "the separation of the history of the earth into chapters should be based, not upon the unconformities, however great, but upon the changes which life has experienced." There may be disagreement with the theory of isostacy as explained on pp. 365 to 368 and applied on pp. 132, 472, 478, and 651.

Little but praise should be expressed for the illustrations in the book, for almost all of them are clear and well chosen. Most of them are new, and this feature will be appreciated. There are, however, a few mistakes connected with the illustrations. Fig. 103 pictures as a peneplain a surface which is now known not to be a peneplain. Figs. 142 and 145 seem to be misplaced; they do not illustrate the work of mountain glaciers. Figs. 396 B and 414 B are both labeled "Receptaculites ohioensis"; fig. 414 B illustrates R. oweni. The illustrations of various principles described in words, which occur throughout the book, are numerous, well chosen, and altogether laudatory.

There is no general plan for presentation of references in the book. Footnotes giving definite references on specific points are practically wanting. A few general references are given at the ends of chapters in Part I and at the ends of smaller divisions within chapters in Part II. In some cases previously published material is quoted, with or without the name of the author, but without specific reference. Much material is taken from classic geological literature without reference; for instance, material on the geomorphology of the Appalachian Mountains, Murray's classification of marine sediments, metamorphism, the bar theory for salt formation, and the Lafayette formation. The book would be of much greater value as a work of reference if more care had been taken with sources.

As in the case of any such work, Professor Cleland's book has its good points and its points of weakness, in which the good points outnumber and outweigh those of the opposite character.

A. C. T.

Mine Waters. By A. C. LANE. Ann. Rept., Board Geol. and Biol. Surv. (1911), pp. 774–779.

The study of mine waters in the copper district of northern Michigan is of practical interest, first, owing to the effect on boilers of the admixture of the lower strongly saline waters with those of upper levels; secondly, because it seems clear that the character of the water has had a considerable importance in the deposition of the copper. Observation

covering most of the eastern portion of the peninsula indicates that beneath (1) the layer of relatively free circulating soft surface waters there is (2) an important horizon of sodium chloride waters, beneath which (3) the water is nearly saturated, in many places, with calcium chloride. It is suggested that the lowest waters are connate, indicating therefore the composition of sea water at the time of deposition of the rocks. The presence of copper chlorides in the lower water, the mode of occurrence of the copper deposits, the chemical character of the alterations of the rock, and the low temperature gradient of the region are all thought to be consistent with the theory that the copper has been deposited in zones of relatively low oxidation by the waters. The ultimate source of the copper must be the formation itself, which as a whole carries about 0.02 per cent copper.

R. C. M.

Le Revermont, étude sur une région karstique du Jura méridional. By GEORGES CHABOT. Ann. d. Géog., XXII (1913), pp. 339–415. Maps 2.

The Revermont is a fragment of the southern Jura Mountains more or less separated from the main part of the range by the valley of the river Ain. While physiographically and structurally an integral part of the Juras, by reason of its position bordering the fertile plains of La Bresse, it is geographically a dependent of the latter. Coralline and foraminiferal limestone of Sequanien to Kimeridgien (Jurassic) age forms the floor of the Revermont valleys, most of which are in the synclines of the highly folded strata. Local conditions make the work of ground-water very important. Large inclosed depressions or sinks into which surface waters drain are characteristic, and comparatively recently the Suran River has dried up completely in the lower part of its course, the water disappearing beneath the surface. The soil is poor and cultivation difficult. Consequently for a number of years there has been a depopulation of the district.

R. C. M.

A New Gypsum Deposit in Iowa. By G. F. KAY, U.S. Geol. Surv., Bull. 580, pp. 59–64, Fig. 11.

The discovery of a deposit of gypsum in the Mississippian rocks of the central southern portion of Iowa is of scientific interest. The gypsum, with some anhydrite, occurs at a depth of more than 500 feet. Whether it will prove to be of economic importance is undetermined.

R. C. M.

The Geology of the County of Jervois, and of Portions of the Counties of Buxton and York, with Special Reference to Underground Water Supplies. By R. LOCKHART JACK. Geol. Surv. South Australia, Bull. No. 3, 1914. Pp. 47, pl. 1, figs. 6, maps 3.

A Review of Mining Operations in the State of South Australia during the Half-Year Ended December 31st, 1913. No. 19. By LIONEL C. E. GEE. 1914. Pp. 66, pls. 6, figs. 3.

The Geology of the Aroha Subdivision, Hauraki, Auckland. By J. HENDERSON, assisted by J. A. BARTRUM. Geol. Surv. New Zealand, Bull. No. 16 (New Series), 1913. Pp. 127, pls. 10, figs. 7, maps and sections 10.

Hauraki is on the northwestern coast of North Island. The report is noteworthy for the description and full analyses of thermal springs of the region. Economically Hauraki is a rich gold- and silver-producing district.

Temiskaming and Northern Ontario Railway Commission. Toronto, 1914. The Mining Industry in That Part of Northern Ontario Served by the Temiskaming and Northern Ontario Railway, Ontario Government Railway. By ARTHUR A. COLE. Pp. 74, pls. 21.

The Geology of Steeprock Lake, Ontario. By ANDREW C. LAWSON.

Notes on Fossils from Limestone of Steeprock Lake, Ontario. By CHARLES D. WALCOTT. Geol. Surv. Canada, Memoir No. 28, 1912. Pp. 23, pls. 2.

Lawson reports the rock to consist of basement complex of granite and gneisses, unconformably overlain by the Steeprock series. This series consists of interbedded traps and volcanic ash, limestone, and conglomerate. Unconformable upon the Keewatin, and in different structural relations from those of the Steeprock series, lie the Seine series of quartzites and conglomerate. These are cut by granite gneiss. Before the deposition of the Seine series, the Steeprock series had been folded down into the older Archean rocks. The Steeprock limestones,

500–700 feet thick, are very fossiliferous. These fossil-bearing strata are placed well down in the Archean, as in the following tabulation:

Algonkian	10. Keweenawan. Erosion interval. 9. Animikie.
	EPARCHEAN INTERVAL
Archean	8. Granite gneiss, intrusive in the Seine series. 7. Seine series. 6. Acute deformation and erosion interval. 5. *Steeprock series. Fossil-bearing.* 4. Erosion interval. 3. Granite gneiss, intrusive in the Keewatin. 2. Keewatin. 1. Coutchiching.

Walcott first identified the fossils as Archaeocyathinae, which are found elsewhere in the Lower Cambrian formations. Later, on the strength of microscopic examination, he called them a new genus, *Atikokania*. He found them apparently related to both the Archaeocyathinae and to the sponge *Syringocnema*. They are quite unlike any of the Beltina fauna. If their stratigraphic position were not surely determined, Walcott would consider them to be of Lower Cambrian age. T. T. Q.

The Huronian Formations of Temiskaming Region, Canada. By W. H. COLLINS. Geol. Surv. Canada, Museum Bull. No. 8, 1914. Pp. 33, pl. 1, figs. 2.

The formations in the "Original Huronian" district have been correlated with the well-known sections at Sudbury and Cobalt. Six type localities were successively studied in the region, and the formations were traced across the intervening spaces. It was certified that the original Huronian sedimentaries consist of two distinct series, separated from one another by a large erosion interval, and separated from the pre-Huronian rocks by a great interval of diastrophism, granite intrusion, and erosional peneplaination. It has been determined that the Cobalt series of Cobalt, the Ramsey Lake conglomerate of Sudbury, and the slate conglomerate of the upper of the two series in the original Huronian are equivalents.

Instead of Upper and Lower Huronian, Collins calls the upper of these series Cobalt and the lower one the Bruce series. Elsewhere, the

name Huronian has been applied to quite different series; by using these local names for the Temiskaming region one avoids confusion.

The Bruce series consists of quartzites, conglomerates, limestones, and greywackes. The Cobalt series contains quartzites, conglomerates, both basal and slaty, and cherty limestone. As at Cobalt, so at Bruce the Cobalt slate conglomerate carries striated bowlders.

T. T. Q.

Über die Parallelstruktur des Gletschereises. By AXEL HAMBERG. 9e Cong. Internat. d. Géog., 1908, Compte rendu II. Pp. 7, pls. 4.

In general two sorts of parallel structure are to be observed in glaciers, that due to the original snow bedding in the collecting area, and that of secondary origin which is vertical and parallel to the longitudinal axis of the glacier. By some it has been thought that the vertical parallel structure was only the original horizontal snow bedding turned up on edge through pressure. It is desirable to know whether "regenerated" glaciers show the vertical parallel structure and how it is formed. The author after a study of a number of glaciers in Sweden and Spitzbergen concludes that the structure in question has relation to the movement of the ice. When there is a downward slope in an ice sheet, the very great downward pressure of the ice from gravity has a forward component which tends to cause movement along the valley. Friction of the sides and bottom of the valley retards the motion of ice layers next to them, so that the ice is broken into parallel bands which move forward at differential rates, the upper central bands moving the more rapidly. The planes of differential motion are influenced by every irregularity of the containing valley and may be trough-shaped.

R. C. M.

The Grain of Igneous Rocks. By A. C. LANE. Ann. Rept., Board Geol. and Biol. Surv., Michigan (1911), pp. 145–71. Figs. 5.

The grain of an igneous rock depends on a number of factors, among which may be noted the chemical and mineralogical composition of the rock, its retention of solvent gases and mineralizers, pressure, and rate of cooling. The last named is one of the most important, and it is observed that there is a direct ratio between the size of the grain and distance from the cooling surface, the effect being most advantageously studied in the mineral grains which are last to crystallize. With due

consideration of certain variable factors, such as the power of crystallization of the magma, diffusivity of heat, production and absorption of latent heat, and undercooling, it is possible to make mathematical determination of the size of grain that should form at a given distance from the cooling surface. Gradual change in the temperature of the margin is one of the factors most difficult to estimate. It seems obvious that the margins of certain even-grained dikes were near the temperature of the magma at the time of crystallization.

R. C. M.

Temperature of the Copper Mines. By A. C. LANE. Ann. Rept., Board Geol. and Biol. Surv., Michigan (1911), pp. 757–73, Fig. 1.

The temperature at various depths in the copper mines is of practical interest because of its importance in determining to what extent men may work with efficiency, and of scientific interest because of its relation to the circulation of mine waters and possibly to the formation of native copper, as indicated by the result of recent experimentation. The mean annual surface temperature in the copper region is about 39° F., that in the upper levels of the mine at the depth of "no variation" between 43° and 44° F. Careful measurements of the rate of increase of temperature downward have been recently made which give an average of 1° F. for 105 feet descent, or in certain cases as low as 1° in 111 feet. This rate is below the normal and may be due to a number of causes. The more important factors are thought to be (1) endothermal reactions connected with the deposition of copper, (2) the high diffusivity of the strata, permitting the free escape of heat, (3) downward absorption of water carrying the cooler surface temperatures, and (4) relative exhaustion of the internal supply of heat by the Keweenawan and earlier eruptions.

R. C. M.